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RADIO PLANNING AND MANAGEMENT OF ENERGY-EFFICIENT WIRELESS ACCESS NETWORKS

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Cette thèse intitulée:

RADIO PLANNING AND MANAGEMENT OF ENERGY-EFFICIENT WIRELESS ACCESS NETWORKS

présentée par: BOIARDI Silvia
en vue de l'obtention du diplôme de: Philosophiæ Doctor
a été dûment acceptée par le jury d'examen constitué de:

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DEDICATION

To my family,
faraway...so close

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The completion of my doctorate dissertation has been a wonderful and often overwhelming journey. I could not say whether it has been grappling with the topic itself which has been the real learning experience, or grappling with how to write papers, give presentations and deal with deadlines... In any case, it is a pleasure to express my thanks to those who contributed in many ways to the success of this study and made it an unforgettable experience.

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RÉSUMÉ

Dans les dernières années, le secteur des Technologies de l'Information et de la Communication (TIC) a transformé la façon dont nous vivons : il joue un rôle principal sur le développement économique et la productivité, en offrant des services innovants qui sont devenus partie intégrante de la vie quotidienne. En raison de ce phénomène, l'effet des technologies de l'information et de la communication sur le réchauffement climatique ne peut plus être ignoré. Le concept des *TIC Vertes* (ou *Green ICT*, en anglais) est né dans le but de stimuler la recherche vers des solutions respectueuses de l'environnement et économes en énergie.

Étant une partie important des TIC, les réseaux de télécommunication connaissent une croissance en plein essor. Les contraintes de qualité de service et de capacité sont les principaux responsables de l'augmentation de la consommation d'énergie ; en particulier, une grande partie de la facture d'électricité des opérateurs de réseaux est due aux exigences élevées de puissance des stations de base sans fil, qui ont été identifiées comme les composantes les plus énergivores des réseaux.

Jusqu'à présent, l'industrie de la communication mobile s'est essentiellement concentrée sur le développement de terminaux mobiles à faible consommation d'énergie afin d'attirer un plus grand nombre de clients et, par conséquent, d'augmenter les profits des opérateurs ; en revanche, le monde de la recherche étudie la question de l'efficacité énergétique d'un point de vue plus large. En plus des études sur *dispositifs* et *protocoles* économes en puissance, des travaux plus récents ont abordé la problème du *design* et du *fonctionnement* éco-énergétiques dans les infrastructures de réseaux câblés et sans fil. De nombreux aspects de la planification et gestion des réseaux verts ont été explorés. Cependant, les deux problèmes n'ont jamais été liés et abordés à la fois, en négligeant le fait que l'efficacité d'une gestion de réseau à faible consommation d'énergie dépend en grande partie des décisions prises dans la phase de design.

La recherche présentée dans cette thèse de doctorat vise à combler cette lacune en développant un système d'optimisation qui considère conjointement le design et la gestion des réseaux sans fil. Le *problème conjoint de planification et gestion énergétique* (Joint Planning and Energy Management, JPEM) proposé ici s'efforce de prouver que le niveau de *flexibilité* offert par la topologie installée améliore fortement la capacité du système à s'adapter à les variations du trafic en étendant les cellules pas nécessaires à la couverture des usagers. En minimisant le compromis entre les dépenses en capital (*Capital Expenditures*, CapEx) dues au déploiement du réseau et les dépenses opérationnelles et de gestion (*Operational Expenditures*, OpEx), calculées sur la durée de vie du réseau, le modèle estime la topologie la plus économe en énergie sujette à des restrictions d'investissement de capital imposées par l'opérateur.

Ce travail analyse deux types de réseaux d'accès. Le problème conjoint de planification et gestion énergétique pour réseaux cellulaires (Joint Planning and Energy Management for Cellular Networks, JPEM-CN) a été développé pour concevoir et gérer l'opération des réseaux cellulaires. Trois tailles de cellules (macro, micro et pico) peuvent être déployées dans une zone sans dispositif d'accès préalable. Un profil de trafic journalier réaliste caractérise la zone en examen ; par conséquent, le trafic offert par les points de mesure (Test Points, TPs) distribués de façon aléatoire dans la région varie dans chacune des périodes considérées. Les résultats numériques obtenus en testant six différents scénarios montrent que, au prix d'une petite augmentation de CapEx, un *réseau planifiée pour être économe en énergie* permet des économies d'environ 50%–60% par rapport à l'énergie nécessaire à l'opération de la topologie de coût minimum. Les résultats donnent aussi un aperçu intéressant sur la composition des différentes topologies. Alors que le réseau de coût minimum est composé de cellules grandes et moyennes, les topologies éco-énergétiques comprennent quelques macro cellules à l'appui de nombreuses micro et pico cellules, qui peuvent être éteintes pendant les périodes de faible trafic sans violer la contrainte de couverture totale.

Un autre système d'optimisation a été modélisé pour résoudre le problème conjoint de planification et gestion énergétique pour réseaux maillés sans fil (Joint Planning and Energy Management for Wireless Mesh Networks, JPEM-WMN). Dans ce cas, deux types de stations d'accès peuvent être placés dans la zone considérée : les routeurs, qui peuvent seulement se connecter à d'autres routeurs, et les passerelles, ayant un accès direct à l'Internet. Un profil de trafic est considéré selon lequel les clients du réseau maillé varient leurs demandes ; également, deux degrés de congestion sont examinés pour le trafic (standard et élevé). Le modèle a été testé sur six scénarios. Bien que les mêmes avantages du JPEM-CN s'appliquent aux réseaux maillés, l'épargne énergétique est moins élevé en raison de la flexibilité moindre de WMNs en comparaison aux réseaux cellulaires hétérogènes. Toutefois, le modèle JPEM-WMN permet une réduction de la consommation d'énergie de 25%–30% dans la plupart des cas avec de faibles coûts d'installation supplémentaires.

Des variations de ces deux modèles de JPEM sont également présentés dans cette recherche. L'un des objectif du travail est d'évaluer l'impact de l'utilisation d'un système de modélisation conjointe, comparativement à une optimisation plus traditionnelle des dépenses d'investissement et une successive gestion de l'opération du réseau. Donc, une *approche en deux étapes* a été développée où le réseau de coût minimum est d'abord installé, et puis géré. Les économies d'énergie mesurés ont servi à évaluer la réduction de la consommation d'énergie obtenue par les versions de JPEM pour réseaux cellulaires et maillés.

Une autre variation importante, formulée pour les deux types de technologie d'accès, consiste à relaxer les contraintes de couverture globale de façon à garantir le service de réseau seulement pour les usagers actifs. Ainsi, les dispositifs d'accès n'ayant que des utilisateurs inactifs dans leur rayon de couverture peuvent être éteints, ce qui diminue encore la consommation d'énergie. Des tests menés des scénarios de réseaux cellulaires ont montré que des épargnes d'énergie supplémentaires de 25%–35% peuvent être atteints, tandis que le pourcentage est d'environ 12% dans le cas des réseaux maillés.

Pour ce qui concerne uniquement les réseaux cellulaires, cette thèse comprend une variation de JPEM-CN où le système n'est pas libre de choisir la meilleure topologie (et donc, les investissements en capital) selon l'importance du coût énergétiques dans la planification du réseau. Un paramètre de budget est plûtot imposé afin de limiter le CapEx à une valeur donnée. Le modèle *Budget JPEM-CN* obtient des résultats similaires à la version originale ; cependant, les nouvelles contraintes de plafonnement des coûts d'investissement rendent le modèle plus complexe.

À propos des réseaux maillés, le modèle *On/Off JPEM-WMN* est présenté où les dispositifs d'accès peuvent changer leur état (d'actif à inactif et vice versa) une seule fois par jour. Cette formulation a pour effet la diminution du gaspillage d'énergie pendant les transitions d'état des stations de base ; néanmoins, l'épargne énergétique dû au mécanisme de deactivation des cellules est inévitablement réduit. D'autres changements mineurs ont également été testés sur le JPEM-WMN au cours de la recherche de doctorat, comme l'introduction d'une capacité variable pour les liens du réseau dorsal, par rapport à la capacité fixe dans le modèle original, et l'élimination des caractéristiques de connectivité multi-hop afin de simuler le comportement d'un réseau cellulaire en ne permettant que l'installation de passerelles.

Afin d' accélérer la résolution de problème conjoint et permettre l'évaluation de scénarios plus proche à la taille réelle, on a mis au point une méthode heuristique ad-hoc où les problèmes de planification et de gestion de réseau, ainsi que les intervalles de temps journalier, sont abordés séparément. A partir d'une topologie complète, l'heuristique trouve le modèle d'activation la plus efficace qui répond aux exigences de couverture à la fois pour la période de trafic de pointe, où des volumes de trafic élevés doivent être servis, et pour le période hors-pointe, où il y a plus de possibilité d'économiser l'énergie en éteignant des stations d'accès. Le modèle d'activation résultant est considéré comme une topologie partielle, qui est fourni en entrée au modèle JPEM-CN original. La topologie initiale est ensuite enrichie pour obtenir la meilleure solution possible pour toutes les périodes de temps. Pour les mêmes scénarios testés dans le cas du réseaux cellulaires, la méthode heuristique a donné des résultats à environ 10% des bornes inférieures des résultats du JPEM-CN ; de plus, de nouveaux scénarios plus grandes ont été testés et résolus avec succès en moins de 15 minutes dans la plupart des cas.

Dans l'ensemble, les diverses formulations de JPEM prouvent que des épargnes énergétiques plus élevés peuvent être obtenues lorsque *la topologie du réseau est conçue pour être* *éco-énergétique*, au prix d'une augmentation modérée des coûts en capital. Pour ce faire, les effets de la gestion du réseau doivent être pris en considération lors de la phase de design du réseau. Par ailleurs, des résultats et des exemples numériques ont montré que la coexistence de plusieurs tailles de dispositif d'accès dans la même topologie est fondamental pour doter le réseau de la flexibilité nécessaire pour s'adapter aux variations de trafic dans le temps et l'espace.

ABSTRACT

In the last years, the information and communication technology (ICT) sector has transformed the way we live. Consistently delivering innovative products and services, the ICT assumed a primary role on economic development and productivity, becoming an integral part of everyday life. However, due to their wide and constantly increasing diffusion, the effect of information and communication technologies on global warming can no longer be ignored. The concept of *Green ICT* has originated with the aim of building awareness of this, thus boosting the research toward environmentally sustainable, energy-efficient technologies and solutions. As an important part of the ICT, telecommunication networks are experiencing a booming growth. Capacity issues and quality of service constraints are some of the main concerns that contribute to raise the power consumption. In particular, a large portion of the electricity bill results from the high power requirements of wireless base stations, which have been proved to be the most energy-hungry network components.

Up to now, the mobile communication industry has focused mostly on the development of power-efficient mobile terminals, so as to attract a higher number of customers and consequently increase the operators' profits; on the other hand, the research world has been investigating energy efficiency from a wider point of view. Besides studies on power-efficient *devices* and *protocols*, more recent works addressed the problem of energy-aware *design* and *operation* in wired and wireless network infrastructures. Many aspects and challenges of green network planning and management have been explored; nevertheless, the two problems have never been linked and tackled at the same time, neglecting the fact that an effective power-efficient network operation largely depends on the decisions taken in the design phase.

The research presented in this doctoral thesis aims at filling this gap by developing an optimization framework that jointly considers the design and operation of wireless networks. The proposed joint planning and energy management problem (JPEM) strives to prove that, when *cell sleeping* is adopted as network management technique, the level of *flexibility* offered by the installed topology strongly improves the system capability to adapt to the varying traffic load. By minimizing the *trade-off* between capital expenditures (CapEx) related to the network deployment and operational and management expenditures (OpEx) calculated over the network lifetime, the model finds the most energy-efficient network topology while meeting the capital investment limitations imposed by the mobile operator.

Two types of access network are analyzed in this work. As the name suggests, the joint planning and energy management problem for cellular networks (JPEM-CN) was developed to plan and manage the operation of cellular networks. Three cell sizes (macro, micro and

pico) are allowed to be deployed in an area where no previous access devices are installed. A realistic daily traffic profile is assumed to characterize the area; therefore, the traffic offered by the test points randomly distributed in the area varies in each time period. Numerical results obtained by testing six different scenarios demonstrate that, with modest CapEx increases, a *network planned to be energy efficient* can reach power savings around 50%–60% compared to the energy saved by managing the operation of the minimum cost deployment. Moreover, the results give an interesting insight on the different topology compositions. While the minimum CapEx network is mostly composed of big and medium size cells, energy-aware topologies include a few larger cells in support of many small cells, which can be put to sleep during low traffic periods without leaving parts of the area uncovered.

Besides JPEM-CN, another optimization framework has been modeled to solve the joint design and operation problem on wireless mesh networks (JPEM-WMN). In this case, only two types of access station can be placed in the area: routers, that can only connect to other routers, and gateways, having direct access to the Internet. Once again, a realistic traffic profile is considered, according to which the mesh clients vary their traffic requests; also, two degrees of traffic congestion are examined, standard and busy. The joint framework were tested on six scenarios. Even though the same benefits of the JPEM-CN apply to mesh networks, smaller energy savings are registered due to the lower flexibility of WMNs in comparison to heterogeneous cellular networks. However, the JPEM-WMN model yields savings of 25% to 30% in most cases with low extra installation costs.

Additional model variants for both JPEM models are also presented in this research. Since one of the objective of the work is to evaluate the impact of using a joint modeling framework compared to a more traditional CapEx optimization and successive network management, a *two-step* approach is developed where the minimum cost network is first installed and then operated. The energy savings served to fairly evaluate the reduction of power consumption achieved by the cellular and mesh versions of JPEM.

Another important variation, formulated for both types of access technology, consists in relaxing the total area coverage constraints to guarantee network service only to the active test points or mesh clients. This way, access devices having only idle users in their coverage radius can be put to sleep, further decreasing the energy consumption: results showed that supplemental power savings of 25%–35% can be reached in cellular test scenarios, while the percentage is around 12% in case of mesh instances.

Referring now only to cellular networks, this thesis includes a JPEM-CN variant where the framework is not free to select the best topology (and thus, capital investments) according to the relative importance of the energy saving component in the network planning. Instead, a budget parameter is imposed in order to limit the CapEx to a certain value. The *Bud-*

get JPEM-CN achieves similar results to the original version; however, the new constraints capping the capital costs seem to add complexity to the model formulation.

For what concerns mesh networks, an interesting *On/Off JPEM-WMN* framework is presented where the access devices can switch their state, from idle to active and vice versa, only once per day, reducing the power wasted during state transitions but inevitably decreasing the energy savings from sleeping cells. Further minor changes have been also tested on the JPEM-WMN during the course of the doctoral research, as the introduction of variable backbone link capacity, compared to the fixed capacity in the original model, and the elimination of the multi-hop connectivity characteristics in order to simulate the behavior of a cellular network, by allowing only the installation of mesh gateways.

In order to speed up the resolution of the joint problem and enable the evaluation of test scenarios closer to real-size, an ad-hoc heuristic method was developed where the planning and operation problems, as well as the daily time intervals, are tackled separately. Starting from a complete topology, the heuristic finds the most efficient activation pattern that satisfies the coverage requirements for both the peak traffic periods, where high traffic volumes have to be served, and the off-peak, where the opportunity to save energy by turning off some access stations is the highest. The resulting activation pattern is considered as a new partial topology, which is provided as input to the original JPEM-CN; the initial topology is then enriched to obtain the best feasible solution for all time periods. For the same cellular test scenarios, the heuristic showed results only about 2% to 13% far from the respective JPEM-CN objective functions; on the other hand, new larger scenarios have been tested and successfully solved in less than 15 minutes in most of the cases.

On the whole, the various JPEM formulations proved that higher energy savings can be obtained when the *network topology is designed to be power efficient* at the cost of moderate increases in capital costs. To do so, the effects of the network management have to be taken into consideration during the network design stages. Moreover, numerical results and examples showed how the coexistence of multiple sizes of access device in the same topology is fundamental to provide the network with enough flexibility to adapt to the traffic variations in time and space.

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LIST OF ACRONYMS AND ABBREVIATIONS

ALR	adaptive link rate
AMPL	a mathematical programming panguage
BCG^2	beyond cellular green generation
BS	base station
CapEx	capital expenditures
CN	cellular network
CS	candidate site
CTP	coverage test point
EM-CN	energy management problem for cellular networks
Globecom	global communications conference
GSM	global system for mobile communications
HSDPA	high speed downlink packet access
ICCCN	International Conference on Computer Communications and Networks
ICT	information and communication technology
IEEE	Institute of Electrical and Electronics Engineers
IG	instance generator
JPEM	joint planning and energy management problem
JPEM-CN	joint planning and energy management problem for cellular networks
JPEM-WMN	joint planning and energy management problem for wireless access networks
LAN	local area network
LTE	long term evolution
MAC	media access control
MAP	mesh access point
MC	mesh client
MR	mesh router
OpEx	operational and management expenditures
QoS	quality of service
RAT	radio access technology
RoD	resource on demand
TP	test point
TTP	traffic test point
UMTS	universal mobile telecommunications system

VoIP	voice over IP
WAN	wireless access network
WDS	wireless distribution system
WLAN	wireless local area network
WMN	wireless mesh network

CHAPTER 1

INTRODUCTION

1.1 Research Context

The constant development and the growing importance on everyday life of the information and communication technology (ICT) industry have stoked the awareness toward ICT power consumption, which inevitably concurs to aggravate the energy crisis and the global warming problem. As reported by thorough studies (The Climate Group, 2008), the telecommunication sector is accountable for between 2% and 8% of the world electricity consumption, almost 50% of which is due to the operation of telecommunication networks (WLANs, LANs, mobile and fixed line networks).

In this context, *green networking* has emerged as a new way of building and managing communication networks to improve their energy efficiency. In Bianzino *et al.* (2012), the authors identify the main motivations as well as the most promising ideas toward a greener evolution of ICT technologies. From the environmental point of view, straightforward solutions imply the use of renewable energy and the design of new components, able to guarantee the same level of performance with a low power consumption. Moreover, energy savings can originate from the rethinking of the network architecture itself: as an example, the displacement of network elements in strategic locations leads to a reduction of the energy transportation losses as well as a higher efficiency in the cooling systems. On the other hand, from an economic point of view, virtual computation units can take advantage of the variability of energy market and customer demand in order to reduce the waste related to power supply. Also, time dimensions (seasons, day/night) can be considered to choose where to execute computationally intensive operations.

The energy consumption scheme presents different characteristics in fixed and mobile networks. In the first case, more than 70% of the overall power is spent in the user segment, while for mobile networks only 10% of the power corresponds to user equipments, while as much as 90% is related to operators' expenses (Koutitas and Demestichas, 2010). Regarding current mobile networks in particular, three major technical drawbacks have been identified (Wang *et al.*, 2012b). Generally, wireless communication techniques are developed to maximize performance indicators such as QoS, reliability or throughput, without taking into account the power consumption of network equipment. Also, mobile networks are overprovisioned, being designed to satisfy the service and quality requirements for peak demand. For instance, it has been measured that, even during high demand hours, 90% of the data traffic is carried by 40% of the cells covering the area (Holma and Toskala, 2009). Network devices are under-utilized for most of the time and, consequently, the energy supplied largely overtakes the real energy needs. Finally, the efforts toward the energy awareness come often at the price of a worsening of the QoS, making the analysis of the trade-off between performance and energy efficiency a primary issue.

Although the responsibility toward the environment represents the principal incentive to investigate on efficient technology solutions, network operators are also interested in reducing the energy waste for budgetary motivations. In fact, they have to cope not only with capital investments related to radio equipment, license fees, site buildouts and installation, commonly identified as capital expenditures (CapEx), but also with running costs such as transmission, site rental, marketing and maintenance (operational and management expenditures, OpEx) (Johansson *et al.*, 2004). The impact of power supply on the overall network OpEx varies widely on the type of device as well as on the site characteristics. As an example, the average proportion of OpEx spent on energy is around 18% in the European market, while the percentage grows up to more than 30% when less mature markets are considered (Lister, 2009). Moreover, the diffusion of mobile telephony and mobile broadband in developed countries, where electricity is often unavailable, entails the deployment of a growing number of off-grid, diesel-powered access stations. Despite the lower capital costs of diesel generators, the high fuel price, together with the high maintenance costs due to the low accessibility of the installation sites, can boost the energy provision expenses up to 50% of the operational expenditures (Correia *et al.*, 2010; The GSMA Association, 2009).

According to Wang *et al.* (2012b); Zeadally *et al.* (2012), the research on green mobile networking mainly focuses on the following aspects.

Data centers in backhaul require an increasing amount of energy to satisfy the growing online storage demand and computational needs. In particular, efforts to reduce the power consumption address the on/off resource allocation, consisting in switching off software and hardware components depending on the traffic load, and the virtualization techniques. In this case, hardware limitations are removed by virtualizing a physical machine on different virtual ones at the same time, with the objective of improving computational efficiency and storage flexibility. Also, research on effective cooling systems and high-efficiency load balancing is important to reduce power waste and optimize the utilization of server resources.

Network devices (routers/switches) are commonly used to connect different types of high-speed networks. Their wide usage implies a constant increase in capacity and performance, together with growing complexity and energy requirements. Power saving approaches are mostly concentrated on exploiting the idle state for unused device components and finding a reasonable trade-off between power usage and performance during active periods.

End-host devices are rapidly evolving from common phones to smartphones and tablets. One of the most important research topic is the so-called “energy profiling”, to give a complete overview of the information regarding power consumption, traffic schemes and local resources of the mobile user system. Other green technologies try to optimize the power efficiency in the utilization of multiple radio interfaces, commonly exploited by modern smartphones or during handoff procedures, or to reduce the energy consumption in transmission mode while maintaining the same level of QoS.

Network protocols efficiency is influenced by two main characteristics: the overhead and the time required to transmit a certain amount of data. Most of the work on wireless network protocols focused on energy-aware routing and MAC techniques.

Applications and services are destined to produce a constantly growing amount of traffic. In order to improve the energy efficiency, some work concentrate on power-saving designs tailored on particular service categories, for example, VoIP or video transmission, while other research studies the historical pattern of specific applications to predict future activity.

Access networks, and in particular *macrocells*, are among the most energy consuming components in mobile networks. In order to mitigate the overprovisioning problem, many recent studies analyze the possibility of turning on and off the base stations (BSs) according to the traffic profile while taking into account quality requirements and system characteristics. Also, cell zooming can vary the cell size to guarantee an effective area coverage and, at the same time, limit the waste of energy and money. Researchers are also investigating how to increase the efficiency of power amplifiers, which are responsible for over half of the energy consumption in the radio segment (Wang *et al.*, 2012b). Also, *femtocells* represent a relatively new solution to minimize power and deployment costs while improving capacity and quality of the connection. Green techniques, in this case, concern power control systems to optimize coverage and energy consumption. Interference avoidance algorithms are important to reduce interference issues between macrocells and femtocells.

1.2 General Objectives and Original Contribution

The exceptional energy consumption of wireless access networks (WANs), which absorb over 80% of the power used in the mobile radio segment (The Climate Group, 2008), is certainly responsible for the great interest devoted by the research world in cells energy efficiency. One need only to consider that the total summed energy consumption of mobile equipment and core network servers has been measured to be 4 or 5 times smaller than the access network

(Blume *et al.*, 2010). Starting from these considerations, the doctorate project proposes and analyzes a new green approach for wireless network design that jointly tackles the following issues.

The first objective is the *definition of location and characteristics of the access devices in a wireless network*. The deployment of network devices over a service area has a great influence in the network operation. Radio planning decisions are usually driven by economic, reliability and performance reasons. Radio access has to be guaranteed everywhere and at all time to mobile users, but the energy consumption factor is rarely taken into consideration during the network design stage.

The second objective concerns the *energy-efficient management of the installed network topology*. Due to the variability of the traffic demand in time and space, and to the fact that service requirements have to be guaranteed for all loads, the network topology results underutilized for most of the time. Putting cells to sleep during low traffic periods can be a powerful instrument to reduce the energy consumption of the deployed cells.

Combining the two problems mentioned above, we introduce a new way to design networks where the power management effectiveness is improved and the expenses related to energy supply are minimized.

In accordance with the research objectives, the following original contributions have been produced along the doctoral program.

Joint Planning and Energy Management Problem for Cellular Networks JPEM-CN

A 0-1 integer linear programming model to jointly plan and manage cellular networks has been developed. To write the joint formulation, the existing studies on network design and management optimization have been examined. Combining the key issues of both problems, the model defines a new set of variables and constraints as well as a new objective function, which constitutes a trade-off between the objectives of the planning and management models. With a weight parameter, it is possible to assign more or less importance to the OpEx with respect to the CapEx, thus obtaining different solutions and associated operation patterns. Three original model variations have been produced:

- *Two-step JPEM-CN*, simulating the more traditional approach where first, the minimum cost network topology is installed, and then, its operational costs are minimized;
- *Partial covering JPEM-CN*, where, differently from any other previous work, the network service is guaranteed only to active customers;
- *Budget JPEM-CN*, where a budget limit is imposed to the CapEx and the network operation costs are individually minimized.

Joint Planning and Energy Management Problem for Wireless Mesh Networks JPEM-WMN

The same concept is extended to wireless mesh networks (WMNs). By exploiting the dynamic features of WMNs, the system is not only cost-effective but also follows the traffic demand in an energy-efficient way during normal operation. The mesh network model includes both binary and integer variables representing the traffic flow between access stations. Again, several original model variants have been developed and tested:

- *Two-step JPEM-WMN*, simulating the more traditional approach where first, the minimum cost network topology is installed, and then, its operational costs are minimized;
- *Partial covering JPEM-WMN*, where the network service is guaranteed only to active customers;
- *On/off JPEM-WMN*, where, to preserve the device functioning and reduce the energy wasted in state transitions, the access station are allowed to change state (from active to sleep or vice versa) only a certain amount of times;
- *Cellular JPEM-WMN*, simulating a cellular network with no multi-hop connectivity;
- *Variable backbone link capacity*, where the wireless link capacity between access stations varies according to the mutual distance.

Ad-hoc heuristic method for JPEM-CN

Due to its complexity, the joint framework for cellular networks requires large computation time to solve the tested instances. In addition, when networks of realistic sizes are considered, the model cannot reach a solution. Therefore, the development of an heuristic method is fundamental to reduce the problem complexity and obtain valuable results also in case of real-size scenarios, with hundreds of possible base station locations and test points.

1.3 Document Structure

Chapter 2 provides first an overview of the main challenges in green wireless networking (Section 2.1); then, a thorough review of the most relevant existing work on energy efficient approaches for cellular and mesh networks is carried out (Sections 2.2 and 2.3, respectively).

A brief introduction of the doctoral thesis motivations and contents is provided in Chapter 3. The current wireless network issues which inspired this work, as well as the original ideas underlying the proposed optimization framework, are stated in Section 3.1. The roadmap of the research is illustrated in Section 3.2. The topics treated in the following chapters correspond to three journal papers published in the course of this doctorate project. Their coherence is highlighted in the context of a thesis by article. Section 3.3 concludes the chapter by providing a short description of the additional work presented in this thesis.

Chapter 4 includes the first journal paper *Planning for Energy-Aware Wireless Networks* (Boiardi *et al.*, 2014), which contains the deepest and, at the same time, most straightforward overview of the whole JPEM framework. After a brief introduction on wireless network design and on the key ideas advanced in the paper (section 4.2), the aspects of the energy efficiency problem in wireless networks are reviewed (section 4.3). Section 4.4 formally presents the JPEM problem and illustrates its basic concepts with the help of simple examples. Section 4.5 describes the characteristics of the cellular and wireless mesh systems that have been used to test the model. Then, we focus on the JPEM implementation and functioning principles. Selected results from both cellular and mesh test scenarios are reported in Section 4.6 to demonstrate the validity and effectiveness of the joint approach. Finally, the chapter ends with Section 4.7, which summarizes the main achievements and proposes possible future work.

The second paper *Radio Planning of Energy-Aware Cellular Networks* (Boiardi *et al.*, 2013) constitutes Chapter 5. Here, the focus is on the JPEM-CN model, developed to design and manage energy-aware cellular networks, its variants and the numerical results obtained from specifically designed test cases. The first part of the chapter is devoted to a general introduction of the power-efficiency in wireless networks (Section 5.2), a condensed presentation of the features of the suggested framework (Section 5.3) and a review of the literature on energy-efficient cellular network management and planning (Section 5.4). Section 5.5 gathers some preliminary considerations regarding the system characteristics, the traffic variability and the propagation model used in the testing phase. The JPEM-CN mathematical formulation is presented and fully described in Section 5.6, while Section 5.7 reports the solution approach, the produced cellular scenarios, the tested problem variations and a large set of pictures and tables displaying results that confirm the effectiveness of the joint optimization method. A summary of the JPEM-CN benefits and characteristics is finally provided in Section 5.8.

The third and last journal paper *Joint Design and Management of Energy-Aware Mesh Netwokrs* (Boiardi *et al.*, 2012b) constitutes the body of Chapter 6. This chapter analyzes the JPEM-WMN, a version of the joint model designed to comply with the mesh network characteristics. Again, several framework variants are presented, as well as a large number of numerical results obtained by trying the model on the produced mesh test scenarios. As for the previous chapters, the article starts off by presenting the energy-efficiency problem and introducing the novelty of the proposed framework (Section 6.2). After a glimpse on the existing work on power awareness in wireless networks (Section 6.3), Section 6.4 describes the mesh system characteristics and the traffic variation. Moreover, two mathematical models, representing the basic approaches to the separate problems of WMN design and operation management, are reported to clarify the origins of the joint formulation. Section 6.5 is dedicated to the exposition of the JPEM-WMN framework, while Section 6.6 illustrates the model variations, the test scenarios and the results achieved by experimenting with all the JPEM-WMN formulations. Section 6.8 terminates the chapter by summarizing the JPEM-WMN qualities and performance.

Additional JPEM forms and results produced during the doctoral project but never published in journal articles are included in Chapter 7. In particular, after a short introduction (Section 7.1), an interesting variation of the JPEM-CN model is presented where the objective function of the joint formulation is broken up and partly replaced by a new set of capital budget constraints (Section 7.2). A slightly different formulation of the JPEM-WMN problem is shown in Section 7.3 where, to preserve the functionality of the access devices and reduce the energy consumed in the on/off transitions, a limit is imposed on the number of daily state changes.

An ad hoc heuristic method for the resolution of the JPEM-CN problem on real-size instances is presented in Chapter 8. The motivations that justify the development of the heuristic are introduced in Section 8.1. The phases of the proposed approach are described in detail in Section 8.2. Section 8.3 shows the results obtained by testing the heuristic on the same scenarios used on the JPEM-CN model, while in Section 8.4 the performance of the proposed technique is evaluated through the resolution of real-size test instances.

This thesis is concluded by Section 10, which gives an outline of the JPEM frameworks and functionality, providing examples of the most striking results for every model variant (Section 10.1). Future work that will support and deepen the research project is also proposed (Section 10.2).

CHAPTER 2

LITERATURE REVIEW

2.1 Green Networking

In the last years, the literature on general green networking has been quickly expanding driven by the groundbreaking work by Gupta and Singh (2003). Here, the authors analyze the main reasons to conserve energy in the Internet and then propose a few possible approaches to reach that objective; in particular, their study focuses on switches/routers and on the possibility of putting to low-power sleep state some of their subcomponents (like line cards, crossbar or main processor). To support their research, they investigated the benefits and feasibility of the different sleeping modes, also mentioning the drawbacks that can appear for selected protocols and possible approaches to fix them. Analogous and enhanced studies on power reduction schemes in network switches have been reported in Gupta *et al.* (2004); Ananthanarayanan and Katz (2008).

From then on, most of the work has focused on power efficiency in wireline networks: some authors have been involved in the development of energy-aware Ethernet (Gunaratne *et al.*, 2006; Gupta and Singh, 2007; Gunaratne *et al.*, 2008; Christensen *et al.*, 2010), others in evaluating the Internet consumption under multiple aspects and in proposals to reduce it (Allman *et al.*, 2007; Mellah and Sansò, 2009; Baldi and Ofek, 2009). For example, Mellah and Sansò (2009) suggests the utilization of *virtualization* and *power management* techniques towards a greener Internet. The first combines different applications to execute them on a smaller number of servers, in order to reduce the hardware and so the energy requirements. On the other hand, energy management techniques are suitable to reduce power waste in legacy networks that are traditionally designed without accounting for energy consumption; in this context, different methods are pointed out as the energy saving mode for network devices or the adaptive variation of the link rate (adaptive link rate, ALR). Redesigning the system in a power-aware fashion or considering the trade-off between reliability and consumption in redundant networks are also considered options. Authors in Baldi and Ofek (2009) tackle the issue from a different point of view, considering *global timing* of network devices and the packet *pipeline forwarding* technique as enabling methods to reduce the electricity bill. Moreover, since at the present time the Internet is based on asynchronous packet switching, they propose the implementation of a *parallel network* coexisting with the current IP one, where a large amount of traffic can be routed fast and with deterministic performance.

A recent and thorough report on the main ideas in green networking research can be found in Bianzino *et al.* (2012) which, besides providing an overview of the energy awareness problem, gives a complete insight into the possible solutions for wired networks, focusing on protocol and performance issues. The impact of green technologies on wireline networks is also evaluated in Bolla *et al.* (2011b). Here the authors identify and analyze two main concepts that underlie most energy saving and power management mechanisms: *dynamic power scaling*, allowing links (ALR technique) and processors to reduce the working rate and meet real service requirements, and *standby approaches*, which permit to network devices to enter a low energy state when traffic load is low. Similarly, Bolla *et al.* (2011a) delves into dynamic adaptation and sleeping techniques, considering also *re-engineering* approaches to introduce and organize new energy-efficient network elements. The three techniques are shown to be applicable to various networks including wired access, wireless/cellular infrastructures, routers and switches, network and topology control, Ethernet, end users and applications. Authors in Zeadally *et al.* (2012) give a complete description of the advances that have been made in the last years to enhance the energy efficiency of the so-called *commodity-based networks* (including Ethernet, WLANs and cellular networks). Without getting down on details on specialized network technologies, the paper presents a detailed literature review on energy management techniques for network equipment (i.e., network adapters), power efficient connecting devices (i.e., routers and switches), data centers and communication protocols. Also, energy issues in last mile access, fixed and cellular networks are discussed, with focus on handoff procedures and BS energy consumption.

Despite the great attention devoted to the infrastructure consumption in wired networks, wireless systems are known to be highly responsible for the power expenditures increase in the ICT sector. Examples of exhaustive reviews of green mobile challenges can be found in Karl *et al.* (2003); Koutitas and Demestichas (2010); Wang *et al.* (2012b). In Koutitas and Demestichas (2010), energy efficient solutions for both fixed and wireless networks are discussed. For cellular networks, the authors use key aspects such as wise network planning and power management, physical layer issues, renewable energy opportunities, and BS operation. Three case studies to improve BS power efficiency are also reported in Han *et al.* (2011): their examples use resource allocation techniques to efficiently exploit RF amplifiers in low traffic conditions, interference management through distributed antenna systems and receiver interference cancellation, use of relays as routing and multi-hop expedients. Other detailed investigations on power efficiency in cellular networks are described in Hasan *et al.* (2011); Correia *et al.* (2010). Besides reviewing the main possibilities to increase BS efficiency, the first paper focuses on network planning based on new communication technologies such as *cognitive radio* and *cooperative relays*, which enable a more efficient use of the radio spectrum and allow improvements in the throughput and coverage issues. On the other hand, Correia *et al.* (2010) analyzes the problem on all levels of the communication system, hence dealing with network level (as architecture and management), link level (as signal processing and discontinuous transmission) and component level aspects (as device efficiency and component deactivation).

In the next sections, the focus will be on cellular and wireless local area networks. In particular, the survey will revolve around network design techniques and power management approaches aiming at limiting the energy consumption of the radio sector.

2.2 Green Techniques for Cellular Networks

Due to the portability of cellular networks, wireless system engineers have always been concerned with energy issues with the aim of improving coverage and battery life. Therefore, there is a very large body of literature focused on energy-efficient devices or energy-aware protocols. The literature on green network planning and operation is more recent, dealing mainly with management as opposed to design issues and always tackling the two problems as separate.

In the last years, some studies on energy-aware cellular network design have been presented; in particular, the efficiency of a radio coverage obtained with the deployment of both macro and micro BS has been at the core of the research debate. On one side, macro cells provide a wide area coverage, but they are not able to guarantee high data rates due to their large coverage radius; on the other hand, given the constantly growing demand of data traffic, the introduction of small, low power and low cost cells appears as an effective compromise. Starting from these observations, Badic *et al.* (2009) measures the power efficiency of a large vs. small cell deployment on a service area by using two performance metrics: the *energy consumption ratio*, defined as the energy per delivered information bit, and the *energy consumption gain*, which quantifies the possible savings obtained employing small cells instead of big ones. The paper of Claussen *et al.* (2008) evaluates the effectiveness of the joint deployment of macro and residential femtocells showing that, for high user data rates, a mixed deployment can reduce up to 60% the annual network energy consumption. Otherwise, when the user demand is mainly voice and a larger number of users can be served by macro BSs, the macro cell coverage appears to be more energy-efficient. Similarly, Richter *et al.* (2009) considers an area where uniformly spread users are served by a macro BS system and estimates the impact of introducing a certain number of micro BSs in each cell. More specifically, the authors measure the area power consumption variation in relation to the inter-site distance and the average number of micro sites per cell. The results show that the power savings are moderate in case of peak traffic scenarios and depend on the offset power of the BSs. A non uniform user distribution is used in González-Brevis *et al.* (2011), where the problem is to find the number and the location (out of a set of predefined sites) of micro stations in order to minimize the long term energy consumption. The results are compared to the case of a single macro BS serving the total number of users, and great power savings are measured for the tested scenario. However, only the power consumption to communicate with the backhaul network and to transmit to the covered users is minimized in the objective function. Authors in Weng *et al.* (2011) consider the problem of insufficient cell zooming, used by active macrocells to extend their coverage area when other BSs are in sleep mode, investigating the possibility of installing an additional layer of smaller BSs. The deployment of an adaptive cell network, where BSs can adjust their coverage radius in relation to the traffic spatial variation, is studied in Qi *et al.* (2010). Here, the service area is divided in dense and sparse zone: the traffic request is intensive in the first one, while in the second one the traffic load is relatively low. This way, the authors strive to reduce the overprovisioning issue in those areas where the coverage and QoS can be satisfied with a lower number of cells. Similarly, Chang *et al.* (2012) analyzes the problem of "coverage holes" that can appear when part of the BSs are turned off to save energy. In particular, considering that neighbor cells may be required to increase their power to compensate for the switched-off BSs, the authors derive the optimal cell size and number of active access stations that minimize the power consumption without violating the complete coverage constraint. A near-optimal algorithm is also proposed for the activation of the minimum number of BSs, which are supposed to be identical and whose position is known.

The energy consumption of an access station has a large floor level, mainly due to processing circuits and air conditioning system, which largely depends to the on/off state of the BS. For this reason, by merely controlling the wireless resources (as transmission power), the power savings are limited. Thus, concerning the energy management aspect of the network operation optimization, a large body of literature addresses the problem of switching off some cells when the traffic is lower. In Chiaraviglio *et al.* (2008b), given the network topology and a fixed traffic demand, the possibility of turning off some nodes to minimize the total power consumption while respecting QoS is evaluated. However, no traffic deviation in space or time are considered. Deterministic and uniformly distributed traffic variations over time are taken into account in Marsan *et al.* (2009), where the energy saved by reducing the number of active BSs when they are not necessary is characterized for different cell topologies. In Marsan *et al.* (2013), a framework to choose the optimal BSs' sleep times as a function of the traffic variation pattern is developed. Considering first homogeneous networks of identical cells, carrying the same traffic and covering the same area, the paper shows how a single sleep scheme per day (from a high-power to a low-power configuration) is enough to guarantee most of the achievable energy savings. The results, divided according to demographic characteristics (business or residential) and time of the week (weekday or weekend), reveal potential savings of as much as 90% in the best cases, while generally reaching values between 30% and 40%. For heterogeneous networks, where a macro cell offers umbrella coverage to a set of micro cells, the authors calculate the optimal order in which the small access devices should enter idle mode. In particular, if the objective is that of minimizing the power waste and the number of BS transients (i.e., from active to sleep state and vice versa), they demonstrate that micro cells should be put to sleep according to growing values of traffic load. The same authors, analyzing three urban area scenarios with different characteristics, show in Chiaraviglio *et al.* (2008a) that it is possible to switch off some UMTS Node-Bs during low-traffic periods, while guaranteeing blocking probability constraints and electromagnetic exposure limits. The HSDPA technology is considered in Litjens and Jorguseski (2010), where a three-step approach to quantify the energy consumption gain when some sites are switched off is proposed. The paper of Zhou *et al.* (2009) considers a random traffic distribution and suggests two algorithms (centralized greedy and decentralized) to dynamically minimize the number of active BSs to meet the traffic variations in both space and time dimensions. Cell size, sleep mode operation and the *vertical sectorization* technique, which allows the deployment of an additional layer of antenna sectors to improve the cell edge performance, are studied in Guo and O'Farrell (2011), while Wang *et al.* (2012a) realistically evaluates the advantages and drawbacks of cell sleeping by taking into account the need to increase neighbor cell transmission power.

Metropolitan areas are normally served by several competing operators, which all provide full coverage of the whole area and dimension networks according to their number of subscribers. However, when traffic is low, the resources of each operator become redundant, while just one of the existing networks would be able to serve all the traffic in the area. In this context, a viable approach is explored in Marsan and Meo (2010): if the operators cooperate, they can switch off their network in turn at the cost of accepting the competitor subscribers as roaming customers while their home network is turned off. Despite some technical complexity and limited additional costs, the potential energy savings can reach 20%. Sama *et al.* (2012) suggests two different signaling frameworks that enable BS pooling between cellular operators without any infrastructure changes, depending on the traffic load experienced by each access station. By means of real test instances, the authors demonstrate that power savings of as much as 66% can be achieved in low load conditions when three network operators are collaborating to reduce the energy consumption. On the other hand, both Lee *et al.* (2005) and Ismail and Zhuang (2011) propose an integration between overlapping mobile cellular networks and WLANs.

Up to now, only a few works approached the problem of optimizing the network deployment and the energy-aware operation at the same time. In particular, the trade-off between deployment efficiency and energy efficiency is pointed out as one of the fundamental frameworks in green radio research in Chen *et al.* (2011), while Chen *et al.* (2010) treats it in more details, defining an analytical relation between the two terms. An approach similar to the one that is at the center of this doctoral research is presented in Son *et al.* (2011). Here, in order to upgrade the network capacity in a cost-effective way, the deployment and management of a micro cell layer overlapping a pre-existing network are discussed. The authors split the problem and propose a two-stage greedy procedure: the first step installs additional micro BSs over a previously installed macro BSs layer for peak demand, while the next one tries to manage the network operation to reduce power waste during off-peak traffic periods. Differently from this work, no pre-existing infrastructure is assumed in the JPEM model, which rather finds what that infrastructure should be by jointly optimizing the planning (BSs location and type) and the energy-efficient operation. Moreover, not only the peak demand but all the varying traffic scenarios are included in the optimization framework.

2.3 Green Techniques for Wireless Mesh Networks

For WMNs, the literature on green techniques is recent and scant. Generally speaking, previous work on WMNs concentrates mainly on MAC and routing protocols, mobility management and security topics. Most of the time, the positions of routers (mesh routers, MRs) and gateways (mesh access points, MAPs) is pre-established and the objective is to optimize the routing or the channel assignment.

Few authors have tackled the problem of planning wireless mesh networks. In Wang *et al.* (2007), only one pre-installed MAP is considered and the location of the minimum number of MRs has to be optimized according to coverage, connectivity and capacity constraints. On the other hand, the modeling approaches proposed in Qiu *et al.* (2004); He *et al.* (2007); Robinson *et al.* (2008) aim at finding the position for the access points given the MR locations. A mathematical model for the complete WMN design is presented in Amaldi *et al.* (2008), where the number and position of MRs and MAPs are selected taking into account typical network issues such as traffic routing and channel assignment. Similarly, Ramachandran *et al.* (2005) studies the MR and MAP planning problem, also approaching key issues such as load balancing, auto-configuration of mesh nodes, single and multipath routing.

In the context of green networking, the only work regarding network operation optimization seems to be Capone *et al.* (2012b). Here, the authors describe an energy-aware management method for WMNs where, starting from a previously deployed topology, the objective is that of minimizing the network power consumption in a time varying context by dynamically switching on and off MRs and MAPs. Differently from this work, the WMN optimization approach presented in this thesis does not consider any pre-existent network infrastructure. Instead, the proposed method aims at finding the network design that guarantees the highest energy savings in the network operation phase while respecting possible budget limitations in the capital investments.

CHAPTER 3

DEVELOPMENT OF THE DOCTORAL RESEARCH

3.1 Motivation

In recent literature, energy-aware mechanisms such as *cell sleeping* are applied to *pre-existing topologies* with the aim of obtaining some power savings under low load. As a matter of fact mobile service providers, which incur not only operational costs (OpEx) but also important one-time installation expenses (CapEx), are hardly willing to invest capital in new and potentially more energy-efficient technologies. Moreover, the extended lifetime of mobile access stations tends to discourage the premature replacement of well-functioning devices. On the other hand, with the worldwide massive diffusion of mobile communications, the opposite problem of managing the continuously increasing traffic demand came to light. A widely accepted solution to this issue (proposed for instance in Richter *et al.*, 2009; González-Brevis *et al.*, 2011), consists in deploying an additional layer of small cells over the existing legacy topology, generally composed by bigger cells, in those areas where the traffic demand is higher. Although often highly overprovisioned, legacy networks are mainly constituted by large, high power access stations with low capacity per unit of covered area. The low installation cost and power usage, as well as the high throughput per unit of covered area by pico cells, make them the perfect candidates to upgrade the network capacity without high expenses by the mobile operator side. When the traffic request decreases, as during nighttime, the small cells can be easily put to sleep without violating the complete area coverage, since they provide extra coverage only in peak time. Conversely the underlying macro cells, the real source of the high energy bill, are unlikely to be turned off due to their large radius which, despite the overlap with neighboring stations, makes them responsible for the coverage of even the smallest portion of service area.

From this scenario, a fundamental problem emerges. In legacy networks, access devices are deployed regardless of energy efficiency considerations: topologies are designed to minimize the capital investments while maintaining the maximum performance in peak load. However, if a power management mechanism is used, the overprovisioned but yet inflexible topology structure prevents the achievement of significant energy savings.

The work presented in this doctoral thesis arises from the belief that a key issue has been so far overlooked by the research on green mobile networking: *network design* and *network operation management* are closely related and interdependent. A good network design can be the key for an effective power saving operation, provided that this is taken into account *during* the planning stages. In particular, the study revolves around the following idea:

Is it possible to improve the network energy efficiency by defining a smarter network design?

To answer this question, an original optimization model was developed which *jointly* considers:

- The network planning, based on a trade-off between CapEx and OpEx;
- The network management, which switch off network cells according to the traffic variations in space and time.

By setting the trade-off value, that is, by assigning higher or lower importance to savings in capital investments or power consumption, different network topologies can be produced. The minimum installation cost deployment can be easily obtained by ignoring the future power expenses; on the other hand, the joint framework is able to compute the best network topology based on its power saving capabilities when slightly higher initial investments are accepted. In summary, the proposed optimization tool allows mobile operators to design the network configuration that best fits their requirements and, at the same time, have an example of the possible benefits derivable from a cell sleeping mechanism applied to the chosen topology.

3.2 Content and Relevance of the Presented Articles

With the exception of the most recent work on the heuristic approach, the research work carried on during this doctorate program has been documented and introduced to the ICT community through two papers presented in the proceedings of international conferences (see Boiardi *et al.*, 2012c,a) and three journal articles (see Boiardi *et al.*, 2012b, 2013, 2014). These make up the body of this thesis, whose schematic is represented in Figure 3.1, while the original contents of the conference papers have been added to the thesis in an additional chapter.

As shown in Fig. 3.1 and expressed in Section 3.1, the concept at the core of the research project is the combination of network deployment and operation management in a single modeling framework, which has been renamed joint planning and energy management problem (JPEM). The general characteristics and benefits of the joint formulation are illustrated in Chapter 4, which reports paper *Planning for Energy-Aware Wireless Networks*, recently published on *IEEE Communication Magazine* (Boiardi *et al.*, 2014). The chapter starts off with a brief overview of the state of the art on energy efficiency techniques applied to wireless networks, providing the reader with key information on green networking and related bibliographic references. The focus is then shifted to wireless network design and, in particular, on the idea that flexibility is the primary characteristic of an effective energy-aware network topology. This notion is clearly explained by means of a simple toy topology drawing. Next, the two version of the JPEM developed for cellular and mesh networks are introduced. First, the main assumptions at the basis of each formulation are illustrated; next, a deeper insight in the JPEM functioning principles is provided. Since the article is targeted at a broader audience than normal scientific papers, no mathematical models are presented; instead, a schematic for both access network implementations is introduced to guide the reader through the description of objective function and constraints. To prove the effectiveness of the joint model, examples of numerical results achieved from a cellular and a mesh network scenario are reported and commented.

Chapter 4 represents a complete, high-level introduction to the JPEM and its foundations, while Chapter 5 constitutes a specific analysis of the joint planning and energy management problem for cellular networks (JPEM-CN) and its results. The paper included in this chapter, titled *Radio Planning of Energy-Aware Cellular Networks* and published in the journal *Computer Netowkrs* (Boiardi *et al.*, 2013), begins by motivating the proposed framework and continues reviewing the most important related work found in the literature. The preliminary assumptions at the basis of the JPEM-CN are then described, regarding: i) the base stations categories, that is, the types of access devices that can be considered in the network design; ii) the traffic variation pattern, representing the traffic changes in time and space during the day and iii) the propagation model used to calculate the area covered by the access stations. At this point, the complete JPEM-CN formulation is examined. First, the sets of parameters and variables are listed and explained; then, the mathematical model is reported and commented. After the introduction of the main features of the test scenarios, generated with the help of a specifically designed instance generator (IG), two important variations of the JPEM-CN are presented. The *two-step* model formulation is intended to compare the joint framework with a more traditional approach where first, the minimum CapEx topology is installed, and then, the operation of the deployed access devices is managed to minimize the energy waste. On the other hand, the *partial covering* variant aims at showing the further energy savings that could be reached if only the active customers required network service, compared to a full and constant area coverage in the original JPEM-CN problem. The last part of the chapter is dedicated to the exhaustive examination of a large set of obtained results, grouped in tables or displayed in multiple figures.

The third article composing this doctoral thesis, titled *Joint Design and Management of Energy-Aware Mesh Networks* and published on the magazine *Ad Hoc Networks* (Boiardi *et al.*, 2012b), is reported in Chapter 6. This chapter focuses on the second variant of the framework, the joint planning and energy management problem for wireless mesh networks (JPEM-WMN). A few paragraphs are dedicated to the description of the mesh system, characterized by multi-hop connectivity, and of the considered traffic variation behavior. Two mathematical models for WMN planning and energy management are then reported in order to provide an example of how the mesh network design and the operation management problems have been separately tackled in previous work. Therefore, the JPEM-WMN is displayed and sets, parameters, variables as well as the objective function and the model constraints are fully described. Multiple model variations were tested for mesh networks and reported in this chapter: i) the *two-step* approach, where the cell sleeping mechanism is applied to a minimum cost, pre-installed network; ii) the *partial covering* variation that, at each time, guarantees network coverage only to those customers that are requesting traffic; iii) the *two-step, partial covering* model, a combination of i and ii where the energy management of the pre-existent network is carried on considering only active clients; iv) the *variable link capacity*, testing the effects of introducing variability in the backbone link capacity according to the distance between two access devices and v) the *cellular comparison*, which simulates a cellular network by eliminating the network's multi-hop capability. Another version of the IG has been developed to generate mesh network instances; after the description of its basic functioning, the test scenario and the values assigned to the system parameters are presented. Finally, a large portion of the chapter is devoted to the analysis and comparison of the results obtained from every model variation.

3.3 Additional Research Work

The papers mentioned in Section 3.2 include a large part of the research carried out during the doctoral program; however, additional tests have been performed to evaluate possible variants and improvements of the original JPEM models. Although this work has not been published in journal articles, the results help to understand the benefits or the flaws of the different models. So, while Chapters 4, 5 and 6 report, respectively, a general discussion on the JPEM framework, a detailed description of the JPEM-CN and a full explanation of the JPEM-WMN and its alternative forms, Chapter 7 focuses on the illustration of two further variations for the JPEM adapted to both cellular and mesh networks. Concerning the JPEM-CN, the model modification proposed in Section 7.2 considers a simpler objective function where only the operational costs are minimized; a limit on the capital investments is now guaranteed by a new set of constraints which cap the CapEx to a predetermined budget value. Numerical results are produced and compared to the ones obtained from the original formulation applied on the same test scenarios. The so-called *Budget JPEM-CN* has not yet been published; on the other hand, the variant of the JPEM-WMN described in Section 7.3 is the primary subject of paper Boiardi *et al.* (2012a). In order to reduce the energy consumed by the network devices during the transition from idle to active state, the mesh network formulation is modified to limit the number of times the access stations can change their state during the day. Once again, the results obtained from the *On/off JPEM-WMN* are illustrated and the main differences with the original JPEM-WMN framework are pointed out.

The complexity of the JPEM formulation for cellular networks represents an obstacle to the possible use of the joint framework on large-scale network planning. In order to allow the solution of real-size instances, an ad-hoc heuristic was developed during the last period of the doctoral research. The heuristic method, presented in Chapter 8 and whose publication is part of the future plans, is based on the separation of the design and operation management problems. First, starting from a complete topology, the most energy-efficient activation pattern is found for the peak and off-peak traffic periods. Then, the activated BSs are considered as a partial topology and provided in input to the original JPEM-CN, which integrates the initial set of access devices to satisfy the capacity and coverage requirements during the whole day. To prove its effectiveness, the heuristic was tested on the same cellular networks solved with the original formulation; moreover, new, large size scenarios have been produced and solved to evaluate the performance of the proposed method and show its possible benefits.

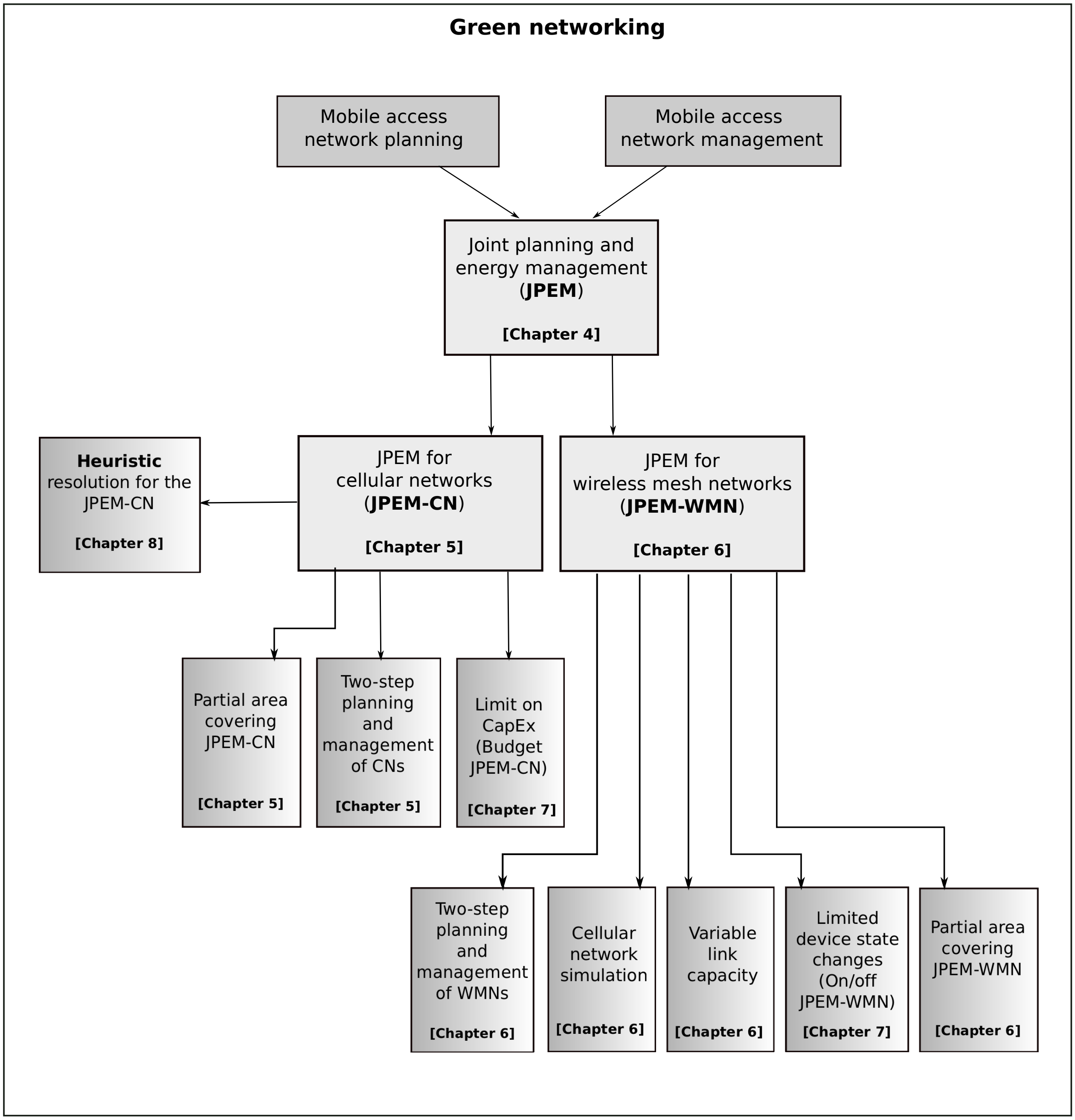

Figure 3.1 Roadmap of the research work.

CHAPTER 4

ARTICLE 1: PLANNING FOR ENERGY-AWARE WIRELESS NETWORKS

Silvia Boiardi, Antonio Capone and Brunilde Sansò
Published on *IEEE Communications Magazine*, February 2014

4.1 Abstract

The paper proposes a fundamental modeling and optimization framework for the planning of energy-aware wireless networks. The key idea is that, in order to produce an energy-efficient network operation, energy awareness should be introduced at the planning stages. Cellular as well as mesh wireless examples are considered.

4.2 Introduction

The rapid spread of mobile telecommunications has pushed not only for the design of new advanced systems, but also for the development of mathematical models and optimization algorithms to support planning and management decisions. Formal optimization methods improve the way the limited resources (e.g., radio spectrum, base stations, antennas, backhauling) are used, and enhance the service quality (e.g., throughput, delay, service accessibility). An important optimization problem is the general *coverage planning*, which consists in determining where to locate the radio access devices and selecting their configuration so that every client in a given area is served. This is usually the main problem addressed by the optimization modules included within mobile operators' software tools for radio propagation estimation and network planning. The typical goal is to minimize the total antenna installation cost while guaranteeing service coverage and quality. A nice view that helps understand the importance of network design optimization for system performance is presented in Eisenblätter and Geerd (2006), where some modeling approaches for wireless network planning problem are analyzed. Hurley (2002) presents an optimization framework for access station location and configuration selection in real size cellular networks, while Eisenblätter *et al.* (2010) tackles the network deployment from the wireless local area network (WLAN) perspective. We refer the reader to the references of the cited papers for more examples.

This paper approaches the wireless network planning from a very different and novel perspective that accounts for *energy efficiency*. In recent years, the rising demand for pervasive information access has in fact underlined the growing ICT power consumption and global warming impact. Almost 50% of the power consumed by the telecommunication industry is due to the network operation (including WLANs, LANs, mobile and fixed line systems). Also, wireless access networks (WANs) are pointed out as the most energy hungry component of the mobile radio segment, being responsible for over 80% of its power absorption (Boiardi *et al.*, 2013). As a consequence, *green networking* has emerged as a new way to design and manage communication networks to reduce power consumption.

Focusing on current mobile access networks, major technical drawbacks have been identified. First, WANs are *over-provisioned* since they are developed to satisfy service and quality requirements in peak traffic conditions. Second, the efforts toward energy awareness come often at the price of a worsening of the QoS, making the analysis of the *trade-off between performance and energy efficiency* a primary issue. There have been some attempts to consider the energy-aware management of wireless networks by first planning a traditional network and then optimizing its power management performance (see Section 4.3). In this article, we convey the new and fundamental idea that energy awareness must be *incorporated at the network planning stages*. Our aim is to demonstrate that the resulting network topology and its operation are different than if planning was carried out in a traditional fashion, leaving the energy management optimization at a later stage. The proposed approach is based on the fact that, when power management is considered, the level of *flexibility* provided by the network topology is essential to adapt the system capacity to the varying traffic load by turning on and off unused access stations.

The framework was applied to both *Cellular Networks* (CNs) and *Wireless Mesh Networks* (WMNs). In what follows, after a brief review of the green network design and management techniques proposed in the literature, we introduce the philosophy underlying the so-called JPEM problem. Then, the considered mobile systems are described, underlining the characteristics which make them good candidates to illustrate our JPEM approach. Also, some details regarding the optimization model formulation and its possible variations are presented, as well as the adopted resolution approach and some example results. Our final remarks conclude the paper.

4.3 Energy efficiency in wireless networks

In recent years, there has been a lot of work on power efficiency in wireless networks. Three macro areas can be identified as the main focus of the research community:

- *Energy-aware network design*, involving issues as the deployment of heterogeneous networks, the use of relays and cooperative communications;

- *Energy-aware network management*, including, for instance, efficient routing techniques able to perform traffic aggregation on a subset of links and devices, cell switch-off, transmission rate switch and multi-RAT (radio access technology) coordination;

- *Energy-aware radio technologies and hardware*, consisting of methods to, among others, improve power amplifiers efficiency (responsible alone for more than half of the access device power consumption), deactivate device components and decrease the energy consumption of spatial diversity techniques.

Excellent surveys which extensively treat those and other energy efficiency topics can be found in Feng *et al.* (2013) and Bianzino *et al.* (2012).

As this paper is centered on network planning and management and not energy-efficient radio technologies and components, we address the interested reader to the cited papers and their references for more information. Regarding the network design research area, different studies on energy-aware cellular networks tackle the efficiency of a radio coverage obtained with the deployment of macro and micro cells. In Badic *et al.* (2009), for example, the authors compare the power efficiency of large vs. small cell deployments on a service area using two performance indicators: the energy consumption ratio, defined as the energy per delivered information bit, and the energy consumption gain, quantifying the possible savings that can be obtained by using small cells instead of big ones. Claussen *et al.* (2008) evaluates the benefits of a joint deployment of macro cells and residential femtocells showing that, for high user data rates, a mixed deployment can save up to 60% of the annual energy consumption of the network. A similar analysis in Richter *et al.* (2009) considers an area where uniformly spread users are served by a macro cell system and estimate the impact of introducing a certain number of micro access stations in each cell. Their results show that, in case of peak traffic scenarios, the power savings are moderate and depend on the offset power of the access devices. A non uniform user distribution is used in González-Brevis *et al.* (2011), where the problem studied is that of finding the number and the location of micro stations in order to minimize the long term energy consumption. The results are compared to the case of a single macro cell serving the total number of users, and great power savings are shown for the tested scenarios.

In the research area of energy-efficient network management, the field studying new device switch-off procedures constitutes one of the most beaten track. The minimum power consumption of a base station (BS) can be significant, due to processing circuits and air conditioning systems. Thus, an effective cell energy management must try to turn off as many devices as possible. Another method is cell zooming, that allows cell size variations to guarantee an effective area coverage while limiting the energy waste.

Summarizing, most green techniques are related to power control systems for coverage and energy consumption optimization (see the references in Boiardi *et al.*, 2013). However, up to now only a few papers proposed a practical approach to address the *energy-aware operation problem in relation to the network deployment.* An example comes from Son *et al.* (2011), where a two-stage greedy approach aims at installing and managing micro BSs over a previously deployed macro cell layer to upgrade the network capacity while limiting the capital expenses. Similarly, in Chiaraviglio *et al.* (2012) the authors use a genetic algorithm to design network topologies according to three different strategies: minimization of the number of BSs, of the consumed power or of both of them. A set of BSs in the total number of installed devices is then selected to be always on, while the remaining stations are managed to save power during off-peak periods.

An interesting, completely new approach to the architecture of mobile networks is currently being investigated by the beyond cellular green generation (BCG^2) project of the GreenTouch initiative (www.greentouch.org), where the separation of signaling and data functions at the radio interface allows to increase flexibility in the use of radio resources and to turn it into higher energy efficiency (Capone *et al.*, 2012a).

4.4 The JPEM Framework

In Figure 4.1, a toy topology made of three cells is depicted. As it happens in real life, we assume that it will be deployed according to a minimum installation cost criterion. The black, bold profile circles represent the area coverage of the turned-on access stations, while thin profile circles stand for turned-off devices. Mobile traffic is concentrated in traffic aggregators, called test points (TPs) and symbolized by black dots, which have to be served (i.e., lie in the coverage area of a switched-on device) at all times. Subfigures 4.1(a) and 4.1(b) report examples of network operation during high and low traffic load, respectively. As we can see in Subfigure 4.1(a), the number of active users during the peak period (say, for instance, around lunch time) requires all access devices to be turned on; on the other hand, Subfigure 4.1(b) shows that during the off-peak period (for instance, late at night), one BS can be turned off to save energy while the other two remain active to serve the user demand. So, in this case, the operational savings correspond to the power spared by switching off the biggest BS. Would it be possible to further decrease the energy consumption of the toy topology? Our answer to this question is represented in Subfigure 4.1(c), where we display the principle of the optimization framework we propose. Knowing the position of the TPs and the variation of their requirement during the day, we exploit this information to deploy a network topology which will be able to better take advantage of the demand fluctuation. If the future operation

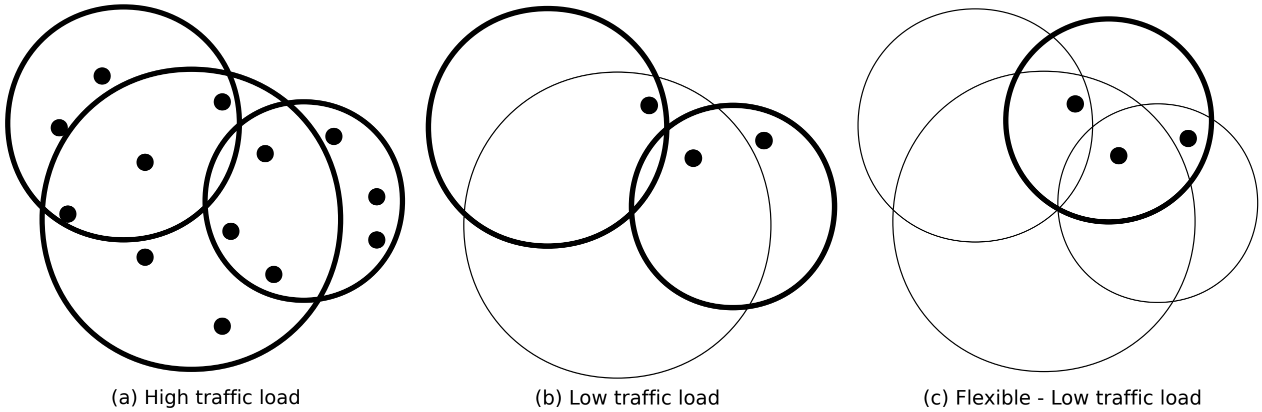

Figure 4.1 Effect of flexibility on network operation management.

management is considered during the planning stage as in 4.1(c), an additional BS should be installed at the cost of a slight increase in installation expenses, so as to be able to switch off a higher number of network devices in off-peak periods (in the picture, three turned-off BSs instead of just one). Our framework philosophy is that, by applying an energy-aware management mechanism on a topology *specifically designed to be power efficient*, the power savings can be highly increased. Therefore, differently from previous work on energy-awareness in wireless networks, we do not assume a pre-existing infrastructure; conversely, to improve the power management effectiveness, we argue that networks should be designed considering the next energy efficiency requirements in the operation phase. The topologies resulting from the application of our method demonstrate our assertions, showing that a real energy-efficient operation strongly depends on the network coverage structure and on the radio planning decisions taken during the design phase.

The JPEM modeling framework is based on exploiting the variety in the types of cellular network access stations and the dynamic features of wireless mesh networks to design a system that is not only cost-effective, but also follows the demand in an energy-efficient way during normal operation. To the best of our knowledge, no previous modeling exist in which energy management is incorporated into wireless network planning optimization. The operating principle of our framework is represented in Figure 4.2, where the proposed problem is depicted as a box having some network information as entry parameters. Such elements constitute the basic information required as input by the JPEM framework: TP and potential BS locations are fixed and known a priori, as well as the estimation of daily traffic patterns and the traffic requirements in the considered time periods. Also, the types and features (power consumption, coverage, transmitted power, installation cost) of the available network devices are specified. Different factors are decisive in the network topology creation. The

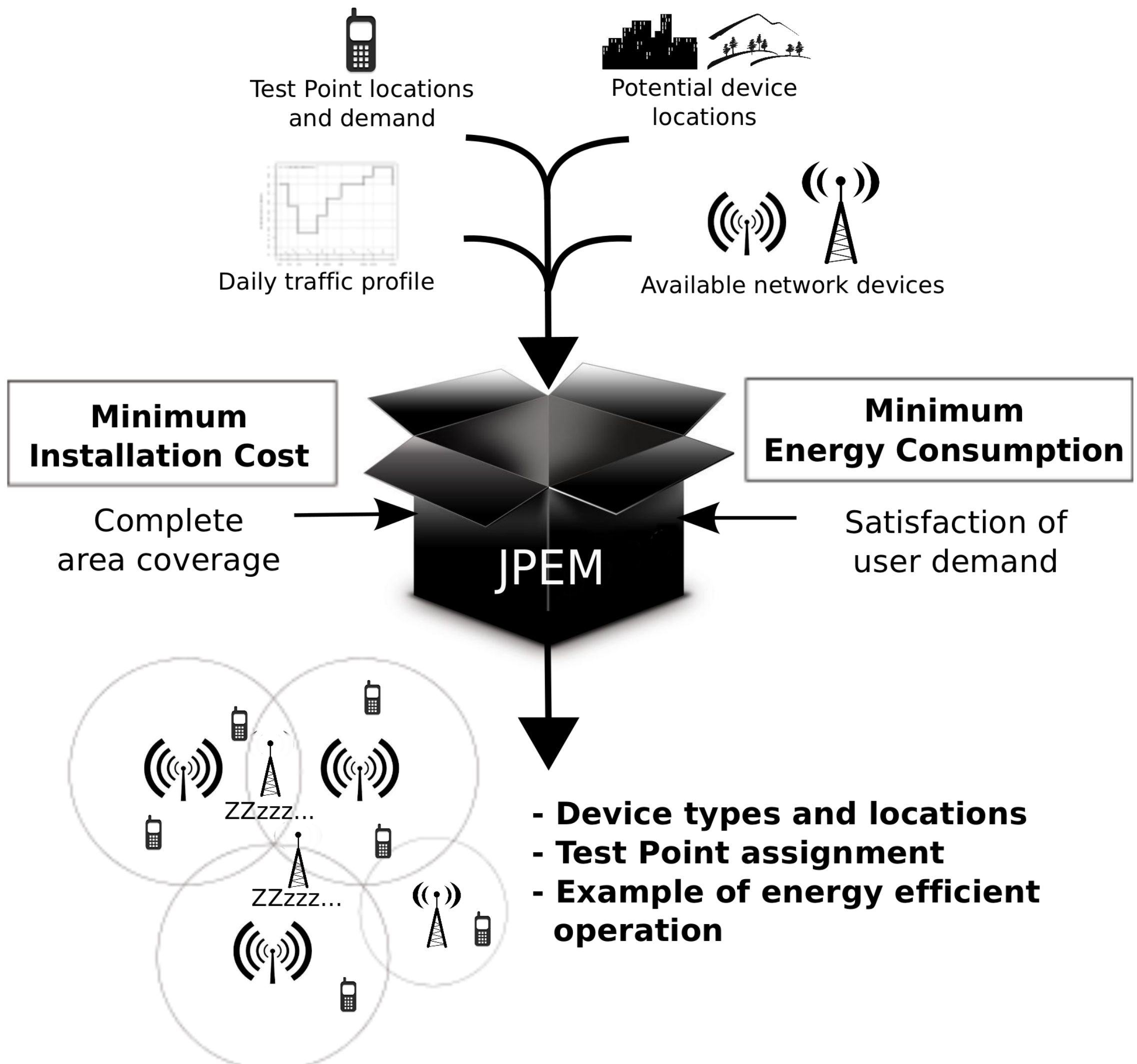

Figure 4.2 Operating principle of the JPEM framework.

main objective of the JPEM is to minimize at the same time the installation costs (capital expenditures, or CapEx), in order to limit the initial investments of the network operator, and the energy spent in the operation phase (operational and management expenditures, or OpEx), so as to guarantee a green, power-aware network behavior. Nonetheless, the complete coverage of the area as well as the satisfaction of the users demand have to be guaranteed at all times. Given these guiding factors, the outcome of the proposed framework consists in an heterogeneous network deployment, where different types of access stations are employed to provide the topology with the flexibility required by a truly energy-efficient operation. test points are assigned to the most convenient access station, according to a distance or signal strength criterion. Also, the JPEM model produces as outcome an example of energy-aware operation of the chosen topology where, in line with the daily traffic pattern, unused BSs are switched off to reduce the power consumption.

4.5 Examples

Two examples illustrate how the JPEM framework can be used to design energy-aware wireless networks and to analyze the trade-off between installation cost and power efficiency. They are based on cellular networks, which are the most important and popular wireless access technologies, and wireless mesh networks, that add the issue of multi-hop coverage.

4.5.1 Cellular Networks

The reference system for the Cellular Network model can be described as follows. Given an area to be served, a set of *Traffic* test points (TTPs) representing traffic centroids is picked out. Besides, a new set of *Coverage* test points (CTPs) is introduced. Differently from the former, they do not produce any traffic; rather, they are disposed on a regular grid overlaying the area to ensure the total coverage in the dimensioning phase even in the off-traffic regions. Together with the TPs, a set of available candidate sites (CSs) where the BSs are allowed to be positioned is identified. Since the signal propagation between any pair of TP and CS can be measured or evaluated, the subset of TPs reached by a sufficiently strong signal is assumed to be known for a BS installed in any CS. In particular, we calculated the median path loss by mean of the COST-231 Hata model. Shadowing and fast fading effects are neglected, which is a common assumption in network design modeling. The framework is however general enough to accept other types of propagation models.

To account for traffic load fluctuation typical of real networks, a *daily pattern* reflecting mobile user habits and representing the active user percentage at each time is considered. The day is then split in periods where the TTP's traffic demand, given by a random value uniformly chosen between a minimum and maximum values, is considered unchanged. Alternatively, TTPs can be in idle state if no traffic is requested. Note that long term demand variations are not taken into account. However, the method is applicable independently of the characteristics of the traffic changes.

Finally, according to the key idea that flexibility is a fundamental characteristic for a power-efficient network, we decided to exploit the diversity offered by the market in terms of cell dimension. Therefore, several *BS configurations* are made available, having different installation cost, capacity, consumed power, transmitted power and coverage.

4.5.2 Wireless Mesh Networks

wireless mesh networks (WMNs) are a type of dynamically self-organized and self-configured communication infrastructures that offer wireless connectivity through the use of cheap and low transmission power devices. Each node in WMNs works as a host as well as a router, forwarding packets on behalf of other nodes that may not be in the transmission range of their destinations. Thus, the nodes automatically establish mesh connectivity among themselves, creating in effect an ad-hoc network.

In the JPEM framework, the mesh reference system is made up of mesh routers (MRs) and mesh access points (MAPs), which communicate through dedicated wireless channels with other access devices residing in their coverage radius. Routers and gateways (generally referred to as BSs) can be installed only in pre-determined CSs. Both kinds of BSs provide network access to mesh users; in addition, MAPs, representing only a restricted set of routers, behave as gateways toward the wired backbone, enabling the integration of WMNs with other networks (typically the Internet). Concerning mesh clients (MCs), they can be assigned to only one BS, being the closest active one, and are connected to the Internet through multi-hop communications.

The day is also divided in time periods during which mesh clients require a fixed amount of traffic. Again, the traffic profile is defined as the percentage of active users typical of every time interval, but in this case two different congestion levels are considered. In addition to the *standard* profile, a *busy* profile has been tested, characterized by a higher value of the minimum user demand.

4.5.3 JPEM Implementation

Let us analyze first the case of cellular networks. From the perspective of power consumption per unit of covered area, a network topology based on small and low-power cells is generally considered more convenient than one deploying only high-power cells. However, since per-site fixed installation expenses tend to prevail, a small cell topology involves high deployment costs. Now, considering that active users must be provided with network service at all time, a cellular system only based on small cells may not be the most energy efficient option; in this case, all cells would be necessary to provide full area coverage and none of them could be switched off during low-traffic periods. Conversely, the availability of different network configurations, employing a set of BSs with different capacity and energy consumption, is what we point out as the key issue to enable effective power management strategies. Such a topology can be obtained only if network planning and operation management are incorporated in the same optimization framework.

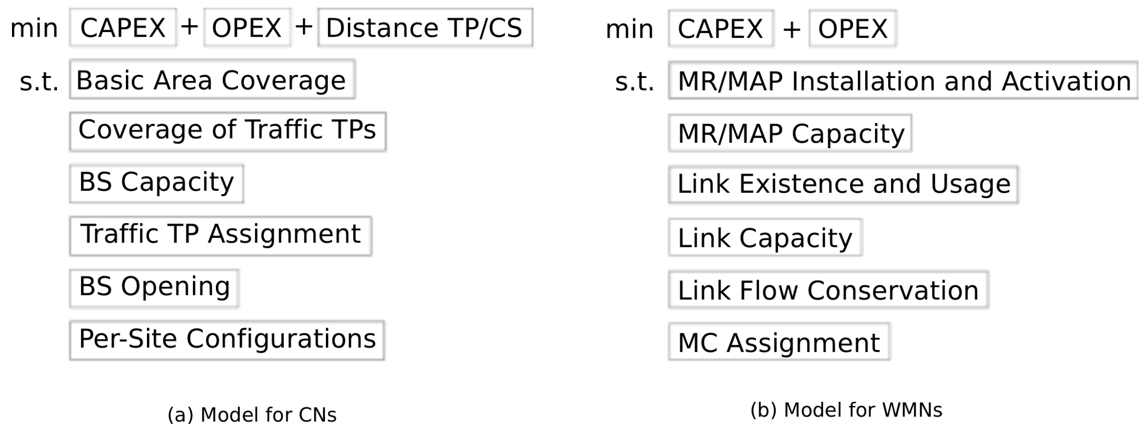

Figure 4.3 JPEM implementation for Cellular and Wireless Mesh Networks.

The JPEM for Cellular Networks (JPEM-CN) is a binary linear programming model to *jointly* plan and manage cellular networks. The schematic of JPEM-CN is reported in Figure 4.3(a), while we refer the reader to Boiardi *et al.* (2013) for the mathematical formulation and further details. Through three sets of binary decision variables, identifying i) the BS configurations installed in the selected CSs, ii) the state (on/off) of every installed BS and iii) the assignment of TTPs to one of the turned-on BSs, the model attempts to minimize an objective function without violating a set of constraints on the variable values. The objective function can be broken down in two main terms. The first one, namely *CapEx term*, accounts for the installation cost of the chosen devices; the *OpEx term*, on the other hand, considers the energy consumption in the operational setting, summing up the power required by each BS during the time periods in which it is turned on. In the cellular context, a third term *distance TP/CS*, to promote the assignment of TPs to the most convenient access device (in terms of distance or signal strength) was introduced in the objective function. Interestingly, that term was active only with GSM technology, whereas it did not have any impact for LTE networks. In order to fairly compare the OpEx term, consisting in a measure of power consumption, with the CapEx one, consisting in a high, one-time cost, the energy related expenses are calculated over the network lifetime (assumed to be 14 years). The trade-off between CapEx and OpEx is adjusted by a weight parameter β, which varies from 0 to any big integer value (typically between 1 and 10). When CapEx are the only costs to be minimized, the value of β is set to 0 to exclude the OpEx term from the objective function: this way, the resulting network installs the minimum cost topology. On the other hand, by choosing higher values for β and introducing the OpEx in the objective function, the model is pushed by the energy management mechanism to reduce at the same time capital and operational expenses. The JPEM-CN framework seeks to minimize the objective function provided that some fundamental constraints are respected. Commonly used in network dimensioning problems, *coverage constraints* provide a basic and constant coverage of the service area, guaranteeing that all the TPs, being Coverage or Traffic ones, lay in the coverage area of at least one switched-on BS (coverage constraints can be relaxed when architecture based on signaling and data separation are considered, as suggested in Capone *et al.*, 2012a). *Assignment constraints* ensure that every TTP is served by one BS in each time period. Traffic TPs in idle state (i.e., that are not requesting traffic in a certain time interval) are as well assigned to a BS, but they do not contribute to fill its capacity. Also note that for Coverage TPs, which never provide traffic, the explicit assignment to an access station is not required. Each access station can route the traffic of a limited number of Traffic TPs, depending on its capacity and therefore on the chosen configuration. So, *capacity constraints* guarantee that active BSs are able to satisfy the traffic demand of the assigned TTPs at any time. Other sets of constraints are introduced in the model formulation, relating the values of different decision variables and fixing their binary domain.

The joint framework for wireless mesh networks (JPEM-WMN) (see Figure 4.3(b) for a schematic and Boiardi *et al.*, 2012b, for the complete formulation) utilizes the same set of decision variables as JPEM-CN: device installation, activation and user assignment. Furthermore, new variables are introduced to keep track of the wireless link existence and usage between MRs, MAPs and the Internet. Once again, the objective function represents the trade-off between the CapEx, corresponding to the installation costs of MRs and MAPs, and the OpEx, calculated as the power expenses of the active devices in any time interval. In this case, the parameter δ weights the relative importance of the two terms by assuming values in the [0,1] interval. Starting from $\delta = 1$, when just capital expenses are minimized, we gradually reached the opposite case of $\delta = 0$ (minimization of power costs only) after evaluating intermediate values. Due to the difference between cellular and mesh system structures, in addition to the well-known sets of *coverage*, *assignment* and *capacity constraints*, different sets of *link* and *traffic flow constraints* are added to the WMN formulation.

4.6 Main results

In order to illustrate the advantages in energy savings achievable by the new planning framework, we show two examples of CN and WMN application. The results are obtained by solving the described linear binary models with CPLEX branch and bound solver, which produced optimality gaps below 5%. Resolution time varied from a few seconds to about half an hour.

Table 4.1 Results from CN Scenario with different values of β.

	$\beta = 0$	$\beta = 0$ (two-step)	$\beta = 1$ (joint)	$\beta = 10$ (joint)
CapEx (k€)	56	56	62 *(+11%)*	66 *(+18%)*
OpEx (k€, 14 years, 0.2€/KWh)	42	39	19	17
OpEx vs. no management	-	*-7%*	*-55%*	*-60%*
OpEx vs. two-step	-	-	*-51%*	*-56%*
Installed BSs	18	18	17	21
BS Type	Macro - 1 Micro - 1 Pico - 16	Macro - 1 Micro - 1 Pico - 16	Macro - 0 Micro - 5 Pico - 12	Macro - 0 Micro - 5 Pico - 16

Table 4.2 Results from WMN Scenario with different values of δ.

	$\delta = 1$	$\delta = 1$ (two-step)	$\delta = 0.5$ (joint)	$\delta = 0.1$ (joint)
CapEx (k€)	9.6	9.6	10 *(+4%)*	12.4 *(+29%)*
OpEx (k€, 14 years, 0.2€/KWh)	17.2	15.6	13.5	13.1
OpEx vs. no management	-	*-9%*	*-21%*	*-23%*
OpEx vs. two-step	-	-	*-14%*	*-16%*
Installed MRs	44	44	46	50
Installed MAPs	2	2	2	6

Tables 4.1 and 4.2 report the total CapEx required by the network deployment and the expected OpEx, calculated over a fourteen-year network lifetime by considering an energy-aware network operation management. Both values are expressed in thousands of Euro, while we assume an energy cost for business users of 0.2 $€/kWh$. The percentages in parenthesis show the CapEx increase with respect to the minimum installation cost topology. Two other sets of percentages are displayed. The first group (third row) indicates the OpEx reduction compared to first column results, while the second group (fourth row) shows the operational cost decrease with respect to the second column ones. The next tables entries represent the number and type of installed BSs, being macro, micro or pico cells in the cellular network case or MRs and MAPs in the wireless mesh network one.

Let us now discuss Table 4.1, where the most important results for a long term evolution (LTE) cellular system scenario are displayed. The service area is a 4 km^2 square, over which 40 CSs, 121 Coverage TPs and 30 Traffic TPs are located. Each traffic demand is a random value uniformly chosen between 20 and 40 Mb/s. The first column, $\beta = 0$, describes the case of a cellular network deployment based on the minimum CapEx network planning where no energy management is performed. A two-step procedure is represented in the second column; here, optimization is first performed without considering the running costs and then, network operation is independently optimized by applying an energy-aware management mechanism to the obtained topology. $\beta = 1$ and $\beta = 10$ correspond to the case of *joint* design and management optimization, where the value of the weight parameter symbolizes the relative importance of the OpEx term with respect to the CapEx one in the model objective function. The most important information included in the table regards the variations in the deployed network when the two-step or joint framework are adopted. By increasing the value of β, and so introducing energy-awareness in network planning, different types and numbers of BSs are installed. In particular, a higher number of medium or small BSs tend to be preferred to macro cells, which have high installation cost and power requirements. Also, from an energy point of view, macro BSs can hardly be turned off to save power during off-peak periods due to their large coverage radius. It appears straightforward that, when we allow the joint framework to account for the network energy consumption at the planning stage, great energy savings are enabled at the cost of a modest increase in CapEx. For instance, with easy calculations we find that when the trade-off parameter is set to 1, the extra capital investment, corresponding to 6000 €, can be recovered in slightly more than four years from the savings in network operation, amounting to 1450 € per year.

The same observations made for cellular networks apply to the wireless mesh network instance reported in Table 4.2. Here, when the trade-off parameter δ decreases, the proposed optimization model is pushed to optimize the network topology and operation in a joint way. On the other hand, if δ equals 1, the less expensive topology from the CapEx perspective is installed and an energy-aware management mechanism can be carried out in a second stage. The WMN scenario displayed in the table includes 240 MCs, requesting a traffic between 1 and 10 Mb/s, and 64 CSs placed over a square area with side 2.5 km. As for Cellular Networks, we notice that a growing number of routers (MRs) is deployed when the operational savings assume more importance than the minimization of the CapEx. Also, when $\delta = 0.1$, four additional MAPs are selected: the power savings are further increased by adding Internet access points, this way limiting the number of hops (i.e., active MRs) necessary for the MC's traffic to reach its destination. Yet again, the OpEx saving percentages confirm the soundness of our framework. However, in this case, we note less striking results due to the fact that WMNs present a limited choice in the device selection, allowing just one configuration of router and one of access point to be deployed. This aspect validates further our initial claim that the network flexibility represents the most important element to enable an effective energy-efficient network behavior.

Results from different test scenarios and interesting framework variations (the relaxation of the total area coverage constraints, among others) can be found in our previous work Boiardi *et al.* (2013) and Boiardi *et al.* (2012b).

4.7 Conclusion

Recent studies on green networking show that a network operation management that follows the traffic variations is one of the most useful instruments to reduce power consumption. In this paper we have shown that, by minimizing at the same time installation costs and operation power expenses, networks are designed for a more efficient energy-aware operation. With the help of some results from Cellular and wireless mesh networks, we showed that an optimal topology from the installation cost point of view does not produce a network that is optimal for an energy-aware perspective. Conversely, the most power-efficient networks include different types of devices, providing the management mechanism with the required flexibility to adapt the network capacity to the user demand in different time periods.

Even though our proposal has specifically focused on energy-awareness on-off operation, it would still be valid for other type of operational issues, such as on-line antenna tilting, for instance (Tipper *et al.* (2010)). In the end, our proposed framework can be summarized in adding and optimizing flexibility at the planning stages for a more efficient and cost-effective operation.

CHAPTER 5

ARTICLE 2: RADIO PLANNING OF ENERGY-AWARE CELLULAR NETWORKS

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Published on *Computer Networks*, September 2013

5.1 Abstract

This paper introduces a joint planning and management optimization approach for cellular networks to limit energy consumption while guaranteeing QoS and minimizing operators' CapEx and OpEx. The modeling framework shows that an effective energy-efficient operation depends on the planning decisions. Conversely, it also shows that planning with energy management operation in view yields more versatile topologies than more traditional models based only on CapEx. Results for LTE networks are provided and show that savings up to 65% in energy expenses are possible with slight increases in capital investments.

5.2 Introduction

It has been reported (The Climate Group, 2008) that the ICT sector is responsible for the world energy expenditures for a percentage that ranges from 2% to 10%. Of particular concern is the consumption of the cellular wireless system, both for its increasing pervasiveness that pushes for more wireless infrastructure and for the well known fact that base stations (BSs) are particularly energy-hungry, representing over 80% of the power used in the radio segment.

While responsibility for climate change is the main push for green networking research, network operators are equally interested in energy consumption reduction for economic reasons. Two types of cost are incurred: CapEx, related to the purchase and installation of radio equipment, and OpEx, consisting on energy, site rentals, marketing and maintenance costs (Johansson *et al.*, 2004). The challenge in terms of energy-aware modeling is to convey both types of cost and power issues into a single modeling framework, which is precisely the objective of this paper. The only example of energy-aware joint design and management method is presented in our recent work Boiardi *et al.* (2012b), where we introduced a similar approach for mesh networks and provided multiple examples and model variations for supporting our thesis. However, to the best of our knowledge, the problem has never been tackled from the cellular network point of view.

The article is divided as follows. In Section 5.3 the modeling framework philosophy is introduced, while Section 5.4 reports general as well as wireless green networking literature. The propagation model, the traffic variations in time and the different types of BSs considered in the model are exposed and discussed in Section 5.5. The model itself, based on mathematical programming, is presented in Section 5.6. The resolution approach, including the instance generation process and some additional tests, is discussed in Section 5.7 together with numerical results, whereas Section 5.8 concludes the paper.

5.3 Proposed modeling framework

From an energy savings standpoint, a radio coverage obtained using small cells served by BSs with low power is considered more convenient in terms of energy per covered area than one with macro cells of high power BSs (this may not be true for all power profiles of devices, but the trend in device technology is going in that direction, Greentouch, 2010). In fact, when the cell radius is reduced, the energy consumption usually decreases faster than the increase of the number of BSs required to cover the area. The opposite is achieved with deployment costs, due to the fact that per-site fixed installation costs tend to prevail. Now, considering that the full coverage of the service area must be ensured at all times, a cellular system based only on small cells may not be the most energy efficient option since all cells are necessary to provide full coverage and none of them can be turned off when traffic is low. On the contrary, the availability of a potentially large number of network configurations, consisting in a set of active BSs having different capacity and energy consumption levels, is the key issue to enable efficient energy management strategies.

Therefore, claiming the key role of network flexibility and stating that energy management *must* be considered when planning the radio coverage of the cellular network, here we propose an approach that jointly optimizes the network design, based on CapEx and OpEx costs, as well as the power management according to different traffic levels.

The traditional models for wireless access network planning - including 2G (Mathar and Niessen, 2000), 3G (Amaldi *et al.*, 2003) and Wireless LANs (Bosio *et al.*, 2007) examples - have to do with finding locations and configuration settings for network devices in order to serve the traffic demand while matching service requirements. The optimal radio planning problem, which consists in determining the best BSs locations out of a set of candidate sites (CSs) while insuring an appropriate signal level, results in the classical minimum cost set covering problem. Taking this basic radio planning model as starting point, we introduce the following innovative features to produce the joint design and management framework: i) The objective function not only includes BSs installation costs (CapEx) but also operational ones

(OpEx), assuming that their variable part is largely due to the expenses related to the energy consumption; ii) Variables and constraints are redefined to include the energy management mechanism in the model and a set of traffic demands related to different time periods of the day is introduced; iii) A trade-off parameter defines the relative importance of CapEx and OpEx in the optimization process and can be used to compare our results with traditional CapEx-only network planning or two-step planning and management approaches (see Section 5.7.3).

5.4 Related Work

Since the seminal work of Gupta and Singh (2003), there has been an expansion in green networking research. Regarding wireless networks, examples of exhaustive reviews of green mobile opportunities can be found in Koutitas and Demestichas (2010); Wang *et al.* (2012b). Three case studies for reducing BS power consumption are reported in Han *et al.* (2011), while other detailed investigations on energy awareness in cellular networks are described in Hasan *et al.* (2011); Correia *et al.* (2010).

Although a large body of literature is focused on energy-efficient *devices* or *protocols*, more recent efforts are on planning or operation, but always tackling the *design* and *management* as separate problems. Considering network operation optimization, a great amount of work has appeared in the last few years. In Chiaraviglio *et al.* (2008b), given the network topology and a fixed traffic demand, the possibility of switching off some nodes to minimize the total power consumption while respecting QoS is evaluated. However, no traffic variations in space or time are considered. Deterministic traffic variations over time are taken into account in Lorincz *et al.* (2010) as well as in Marsan *et al.* (2009), where the energy saved by reducing the number of active access devices when they are not fully utilized is characterized for different cell topologies. In Chiaraviglio *et al.* (2008a) the authors show that it is possible to switch off some UMTS Nodes in urban areas during low-traffic periods, still guaranteeing quality of service constraints in terms of blocking probability and electromagnetic exposure limits, while authors in Zhou *et al.* (2009) consider a random traffic distribution and dynamically minimize the number of active BSs to meet the traffic variations in both space and time dimensions. Moreover, Weng *et al.* (2011) examines the *cell zooming* problem (i.e., the extension of a cell coverage area to guarantee service when other BSs are turned off) and assesses the possibility of modifying the cell deployment to allow higher power savings by turning off a greater number of BSs.

For what concerns network planning, Badic *et al.* (2009) measures the power efficiency of a large vs. small cell deployment on a service area by the help of two performance metrics: the *energy consumption ratio*, defined as the energy per delivered information bit, and the *energy consumption gain*, which quantifies the possible savings obtaining using small cells instead of big ones. In Qi *et al.* (2010) the authors divide the service area into dense and sparse zones and propose an adaptive deploying strategy where the size of the cells can be adjusted according to the varying user requests. Paper Claussen *et al.* (2008) evaluates the effectiveness of the joint deployment of macro cells and residential femtocells, while Richter *et al.* (2009) investigates the cells layout impact on power consumption by varying the numbers of micro BSs per cell in addition to conventional macro sites. The results they provide show that the power savings are moderate in case of peak traffic scenarios and depend on the offset power of the BSs. Unlike such work, we do not limit our analysis to regular layouts and we propose an optimization approach that can be used with arbitrary topologies and propagation scenarios.

Up to now, only a few articles approached the problem of optimizing the network deployment and the energy-aware operation at the same time. In particular, the trade-off between deployment efficiency and energy efficiency is pointed out as one of the fundamental frameworks in green radio research in Chen *et al.* (2011), while Chen *et al.* (2010) treats it in more details, defining an analytical relation between the two terms. Another approach in the use of micro cells overlapping a pre-existing network is discussed in Son *et al.* (2011), where a two-stage greedy approach is used to upgrade the network capacity while limiting the required expenses. In the first stage, additional micro BSs are installed over a previously deployed macro cells layer to meet peak traffic demand; then, the network operation is managed with the aim of reducing power waste during off-peak periods. Differently from that article, we do not assume a pre-existing infrastructure but rather find what that infrastructure should be by jointly optimizing the planning (BS location and type) and the energy efficient operation. Moreover, not only the peak demand but all the varying demand scenarios are included in the optimization framework. A similar two-stage planning and management technique is also adopted in Chiaraviglio *et al.* (2012). Here, the authors exploit a genetic algorithm to design network topologies according to three different strategies: minimization of the BSs number, of the consumed power or of both of them. A set of BSs in the total number of installed devices is then selected to be always on, even during off-peak traffic periods; the next step consists in managing the remaining access stations in order to save power when traffic is low. BSs are turned off according to two criteria: least loaded (lower number of served users) and most overlapped (highest portion of coverage area shared with neighbor BSs). In our work, contrarily, we adopt a one-step approach to point out the benefits and the topology changes that can be obtained when the network design and management are optimized in a joint fashion.

5.5 Preliminaries

5.5.1 Base Station Categories

In order to verify our claims and evaluate the proposed approach, we considered LTE technology test scenarios. Since we stated that network flexibility is a key factor to obtain an effective energy-efficient network management, three different BS types (called here *configurations*) are taken into account, each one allowing to be switched off in case of low traffic profile. Realistic power consumption and capacity values for BSs have been extracted from Imran (2011) and collected in Table 5.1, where the heading "Consumed Power" represents the mean equipment power consumption (including power amplifier, signal generator, air conditioning and microwave link). Note that we provide specific BS categories to create interesting numerical examples, but the proposed design approach is general and can be used with any mix of BS types and technologies.

5.5.2 Traffic Variation Behavior

Intuitively it can be said that traffic intensity varies as a natural effect of users daily habits. For example, it has been measured that mobile traffic presents its peak between noon and 4 pm and that there is a significant decrease in the late evening. Moreover, in a typical business area, the traffic pattern is almost the same from Monday to Friday but it decreases during the weekend (see Heegaard, 2007). To account for the main fluctuations, but neglecting the differences that occur between working and weekend days, we consider an approximated daily pattern based on the downlink traffic measurements presented in Imran (2011). According to this profile the whole day is split in time periods, each one gathering smaller intervals (hours) in which the users behavior can be assumed unchanged. We define T as the ordered set of time periods, with δ_t representing the length of period $t \in T$. The end of each time period is equal to the beginning of the new one, so that there is no time gap between adjacent periods and the summed duration of all periods is equal to the number of hours in a day. In this paper, we assume a total of eight time periods for our LTE examples. Observing Figure 5.1, the progress of the approximated traffic profile defines active user percentages in every time interval.

In more detail, our traffic distribution is modeled as follows. Let us define a test point (TP) as an aggregated traffic centroid. From now on, we will refer to typical TPs with the name of *Traffic* test points. For each Traffic TP we calculated a random value uniformly chosen between 20 and 40 Mb/s, together with a random number in the $[0, 1]$ interval. The first value is fixed, denoting the traffic amount that each Traffic TP provides to the network only if the second number is less or equal the normalized traffic value. Furthermore, in our modeling

Table 5.1 Transmission and consumption features of each BS configuration.

Configuration	Installation Cost (€)	Transmitted Power (dBm/W)	Consumed Power (dB/W)	Traffic Capacity (Mb/s)	Coverage Distance (m)
$C1$	30000	43 / 19.9	31.3 / 1350	210	1230
$C2$	10000	38 / 6.3	21.6 / 144.6	70	850
$C3$	1000	21 / 0.1	11.7 / 14.7	70	241

framework we introduce a new kind of *Coverage* test points, disposed on a regular square grid overlaying the whole area. Coverage TPs do not produce any traffic but, since they have to lie in at least one active cell, they are essential to ensure the total area coverage in the dimensioning phase even in the off-traffic regions.

5.5.3 The Propagation Model

Although, in real scenarios, the transmitted signal quality is affected by path loss, shadowing and fast fading, a common assumption in network modeling consists in omitting shadowing, while we neglect fast fading because of the characteristics of our problem (small-scale variations are fairly rapid in space).

Being f (2600 MHz) the operating frequency, h_b ($12\,m$, $10\,m$ or $8\,m$ according to the BS configuration) and h_r ($1.5\,m$) the correction factors for BS and user antenna height, the median path loss at a generic distance d is calculated by using the COST-231 Hata model (Hata, 1980):

$$\begin{aligned}\overline{PL}(d)[dB] = 46.3 + 33.9\,Log(f) - 13.82\,Log(h_b) - a(h_r) + \\ + (44.9 - 6.55\,Log(h_b))\,Log(d) + c_m.\end{aligned} \tag{5.1}$$

The parameter c_m is equal to zero for suburban areas, while the function $a(h_r)$ is defined as:

$$a(h_r) = (1.1\,Log(f) - 0.7)h_r - (1.56\,Log(f) - 0.8). \tag{5.2}$$

Finally, cable losses are 2 dB while antenna gains are assumed to be 15 dB for configurations $C1$, $C2$ and 12 dB for $C3$.

5.6 The Joint Design and Management Framework

Let us define the model *parameters:*

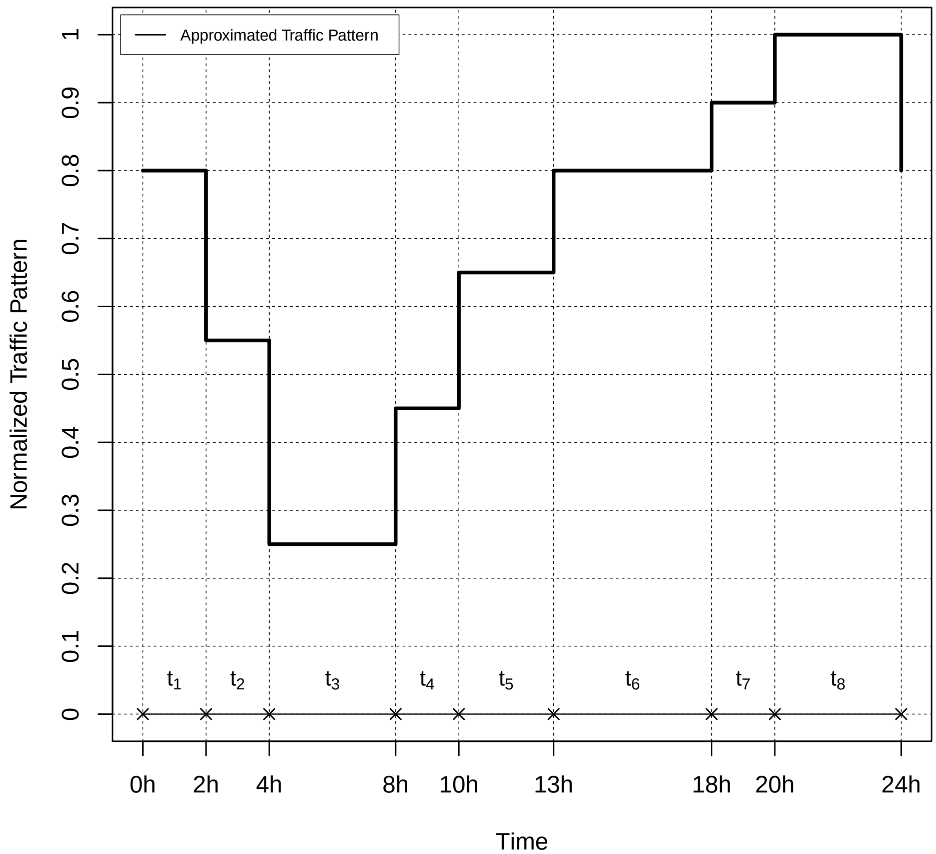

Figure 5.1 Approximated traffic profiles for LTE systems.

I_c : Set of *Coverage* TPs, which do not generate any traffic but help provide a basic, fixed network coverage even in case of very low traffic profile.

I_t : Set of *Traffic* TPs, which allow the network to "follow" traffic changes in the different time periods by generating variable traffic.

S : Set of available CSs for the BSs.

K_j : Set of possible configurations for a BS located in site $j \in S$.

T : Set of time intervals.

δ_t : Duration of time period $t \in T$.

p_{it} : Traffic provided by the Traffic TP $i \in I_t$ in period $t \in T$.

c_{jk} : Capacity of the BS located in site $j \in S$ with configuration $k \in K_j$.

γ_{jk} : Installation cost for a BS located in site $j \in S$ with configuration $k \in K_j$. This is composed of the cost due to the characteristics of the chosen site (for example, open spaces or buildings) and the cost specific for the selected configuration.

ϵ_{jk} : Power consumption for a BS located in site $j \in S$ with configuration $k \in K_j$.

r_{ij} : Distance between the Traffic TP $i \in I_t$ and the BS located in site $j \in S$.

φ : Cost of the energy consumption over the entire network life. This parameter is defined as $E \cdot 365 \cdot n \cdot 0.001$, where E represents the energy cost (€) per kWh, n stays for the years over which the OpEx costs are computed (365 days in a year), and the factor 0.001 is used to convert from Wh to kWh. In this paper, we will consider $E = 0.35$ €$/kWh$ and $n = 8$, which lead to $\varphi = 1$.

β, ϑ : Weight parameters that will be used for trading-off the objective function.

To conclude the model parameters, we need to introduce a binary one that summarizes the coverage information for each combination of TP and CS:

$$a_{ijk} = \begin{cases} 1 & \text{if TP } i \in I_c \cup I_t \text{ is in the coverage area of a BS} \\ & \text{ installed in } j \in S \text{ with configuration } k \in K_j, \\ 0 & \text{otherwise.} \end{cases} \tag{5.3}$$

Let us now define the z, y and x *decision variables* that represent, respectively, the choice of BS location and configuration type, the BS status (active or idle) and the TP assignments:

$$z_{jk} = \begin{cases} 1 & \text{if a BS is installed in site } j \in S \text{ with configuration} \\ & k \in K_j, \\ 0 & \text{otherwise.} \end{cases} \tag{5.4}$$

$$y_{jkt} = \begin{cases} 1 & \text{if a BS installed in site } j \in S \text{ with configuration} \\ & k \in K_j \text{ is active in period } t \in T, \\ 0 & \text{otherwise.} \end{cases} \tag{5.5}$$

$$x_{ijt} = \begin{cases} 1 & \text{if TP } i \in I_t \text{ is assigned to a BS in site } j \in S \text{ in} \\ & \text{period } t \in T, \\ 0 & \text{otherwise.} \end{cases} \tag{5.6}$$

Then, the JPEM-CN can be defined as follows:

$$\min \quad \sum_{j\in S}\sum_{k\in K_j} z_{jk}\gamma_{jk} + \beta\,\varphi \sum_{j\in S}\sum_{k\in K_j}\sum_{t\in T}\epsilon_{jk}\delta_t y_{jkt} + \vartheta \sum_{i\in I_t}\sum_{j\in S}\sum_{t\in T} x_{ijt}\delta_t r_{ij} \tag{5.7}$$

$$\text{subject to:} \quad \sum_{j\in S}\sum_{k\in K_j} a_{ijk}y_{jkt} \geq 1 \qquad \forall i \in I_c \cup I_t, t \in T \tag{5.8}$$

$$x_{ijt} \leq \sum_{k\in K_j} a_{ijk}y_{jkt} \qquad \forall i \in I_t, j \in S, t \in T \tag{5.9}$$

$$\sum_{i\in I_t} x_{ijt}p_{it} \leq \sum_{k\in K_j} c_{jk}y_{jkt} \qquad \forall j \in S, t \in T \tag{5.10}$$

$$\sum_{j\in S} x_{ijt} = 1 \qquad \forall i \in I_t, t \in T \tag{5.11}$$

$$y_{jkt} \leq z_{jk} \qquad \forall j \in S, k \in K_j, t \in T \tag{5.12}$$

$$\sum_{k\in K_j} z_{jk} \leq 1 \qquad \forall j \in S \tag{5.13}$$

$$z_{jk} \in \{0,1\} \qquad \forall j \in S, k \in K_j \tag{5.14}$$

$$x_{ijt} \in \{0,1\} \qquad \forall i \in I_t, j \in S, t \in T \tag{5.15}$$

$$y_{jkt} \in \{0,1\} \qquad \forall j \in S, k \in K_j, t \in T \tag{5.16}$$

The objective function (5.7) is composed of three parts: the CapEx term, which accounts for the equipment installation costs, the OpEx one, that considers the energy expenses over the entire network lifetime, and a final term to guarantee a better connection quality between users and antennas. In the case of the results presented in this paper, however, we verified that the third component, introduced to push the assignment of each TP to the nearest available BS, does not have any influence on the choice of the serving BS. For this reason, we set the trade-off parameter ϑ to 0. On the other hand, by playing with the trade-off parameter β, the relative weight of the CapEx and OpEx components can be modified. Setting β to 0, OpEx costs are excluded from the objective function and only the installation investments are minimized: the resulting network will deploy a minimum cost topology. When β is equal to 1, the energy management mechanism is enabled and forces the model to reduce not only capital but also operational costs by introducing the OpEx term in the objective function. Finally, higher values of β show the network topology changes and the greater energy savings that can be obtained when growing importance is given to the OpEx component. Concerning constraints, we introduce two sets of *coverage constraints*. (5.8) provide a minimal, constant coverage by ensuring that all the TPs are within the service area of at least one active BS, while (5.9) assign Traffic TPs only to a BS they are covered by. *Capacity constraints* (5.10) guarantee that each active BS can satisfy the traffic demand of the assigned Traffic TPs and *assignment constraints* (5.11) impose that every Traffic TP is assigned to only one BS. (5.12) are *linking constraints* between variables y and z, while *configuration constraints* (5.13) impose that at most one BS configuration is installed in a CS. Finally, (5.14), (5.15) and (5.16) impose the binary values for the decision variables.

JPEM-CN, which is a linear binary problem, is NP-hard.

5.7 Resolution Approach and Numerical Examples

5.7.1 Instance Generation

The proposed mathematical model was implemented on AMPL and solved with CPLEX branch and bound solver (CPLEX, I.B.M., 2010), which produced optimality gaps below 5% for the experimented instances. The resolution time ranged from a few seconds to approximately half an hour, depending on the value of β and on the scenario dimension. To test the effectiveness of the proposed model, we designed and implemented in C++ an Instance Generator which creates realistic cellular network scenarios where the number of CSs and TPs is similar to the one that can be found in real networks. The features of our test scenarios are described in Table 5.2: the first entry represents the area size (expressed in square kilometers), the second one is the number of CSs randomly located in the considered region and next are the number of Coverage TPs (CTPs), placed on a regular grid which covers the service area. The last entry displays the number of Traffic TPs (TTPs), evenly randomly positioned in the whole area (Scenario 1 and 2) or placed with a higher probability in a smaller region that can represent, for example, a built-up area in the countryside or the center of a big city (Scenario 3-3a-3b-3c). For every scenario, different values of the weight parameter β were tested: by doing so, we strove to highlight the benefits achieved by jointly minimizing costs and power expenditures in the design and management phases, instead of limiting the optimization at the network planning stage.

5.7.2 Additional Tests

In order to evaluate the value of the proposed approach, we compared our results with those obtained by separately optimizing, first, the network design, and then, the network management. The common *two-step* approach has been reproduced by adapting our model in the following steps:

1. Run the JPEM-CN with $\beta = 0$ to choose the minimum cost topology without considering the energy management;

Table 5.2 Parameters used to generate the test scenarios.

	Area (km^2)	CSs	CTPs	TTPs	Allowed Configurations
Scenario 1	2×2	40	121	30	All
Scenario 2	5×5	60	676	60	All
Scenario 3	4×4	120	441	40	All
Scenario 3a	4×4	120	441	40	C1, C2
Scenario 3b	4×4	120	441	40	C1, C3
Scenario 3c	4×4	120	441	40	C2, C3

2. Fix variables z_{jk} according to the results of the previous step: this way, locations and characteristics of installed BSs will be defined;

3. Run the joint model where z_{jk} are no longer variables but parameters set according to step 2 (network topology is already defined) and the CapEx term is excluded by the objective function.

Moreover, since data traffic in cellular networks is typically *bursty* (that is to say, users are likely to provide traffic only in certain time intervals, while they are silent for the rest of the time), we observed that greater energy savings could be reached if the network service was limited only to active Traffic TPs. So, as JPEM-CN, this problem variation aims at providing a full-coverage network deployment, but now the objective is that of guaranteeing service only to the users that are requiring traffic in any time period, allowing to turn off those BSs which have only inactive users in their coverage region. To model the *partial coverage* approach, we need to introduce a new set of binary parameters m_{it} that are equal to 1 if Traffic TP i is active in time period t. Then, constraints (5.8) in the original model are replaced by:

$$\sum_{j \in S} \sum_{k \in K_j} a_{ijk} z_{jk} \geq 1 \qquad \forall i \in I_c \cup I_t, \tag{5.17}$$

meaning that every Coverage or Traffic TP has to be covered by an *installed* BS, regardless of its on or off state, while constraints (5.11) become:

$$\sum_{j \in S} x_{ijt} = m_{it} \qquad \forall i \in I_t, t \in T, \tag{5.18}$$

since network service is provided only to active clients. The partial coverage problem can be written as:

$$\begin{aligned} \min \quad & (5.7) \\ \text{subject to} \quad & (5.9), (5.10), (5.12) - (5.18). \end{aligned}$$

Note that the partial coverage case cannot be implemented in current mobile network technologies where continuous and full coverage must be ensured. However, new access architectures have been recently proposed and are currently being considered by standardization bodies where the control and data plane are separated at the the radio interface (Capone *et al.*, 2012a). Such a separation allows data BSs to be turned off when no active user is under their coverage area, since a continuous access availability is guaranteed by the always-on signaling BSs.

5.7.3 Numerical Results

In order to appreciate the results of the joint approach and the differences with the two proposed variations, in what follows we concentrate mainly on pictures representing some important results from Scenario 2. Traffic TPs are symbolized by black dots, while Coverage TPs are arranged on a regular grid every 200 m. Only selected CSs are depicted: switched-on BSs are represented as black triangles, while switched-off BSs as white ones.

Let us focus on Figure 5.2, which displays the network obtained for Scenario 2 when the CapEx and OpEx are optimized in two separate steps. Since in the first step only capital costs are minimized, the network planning recalls the capacitated facility location problem and the installed BSs represent the minimum cost network topology. We note that as much as 5 type $C1$ BSs are deployed and, together with 11 additional type $C2$ BSs, they can cover the whole area. However, due to the fact that the traffic required by Traffic TPs is high compared to BS capacity, 7 type $C3$ antennas are also required to serve the users demand. Despite the apparently effective operation of the energy aware mechanism (see Figure 5.3, displaying the turned-on BS during off-peak traffic period), the OpEx expenses are just slightly lowered, if compared to the non-managed network operation; in fact, only the smallest and least power consuming BS can be turned off, while the biggest BS have to guarantee the area coverage at all times. Figures 5.4 and 5.5 show how the joint design and management model modifies the network topology and operation chosen for Scenario 2 by the separate approach. The first picture represents the network behavior in the peak-traffic time period t_8 when β is set to 1. Differently from the two-step case described above, 30 BSs instead of 23 have been installed at the cost of a 4% CapEx increase, corresponding to 10000 €. Due to a lower installation cost per covered square kilometer (4405 €, compared to 6315 € for $C1$ and 5494 € for $C3$), most of them are type $C2$ (21), while 2 type $C1$ and 7 type $C3$ cells are still necessary to guarantee the total area coverage and support intermediate BSs serving TPs traffic.

The network management mechanism achieves more striking energy and cost savings if we allow a BS to be turned off when it has no active Traffic TPs in its coverage area. In this case, no network service is supplied to silent users; however, due to the full coverage nature of the

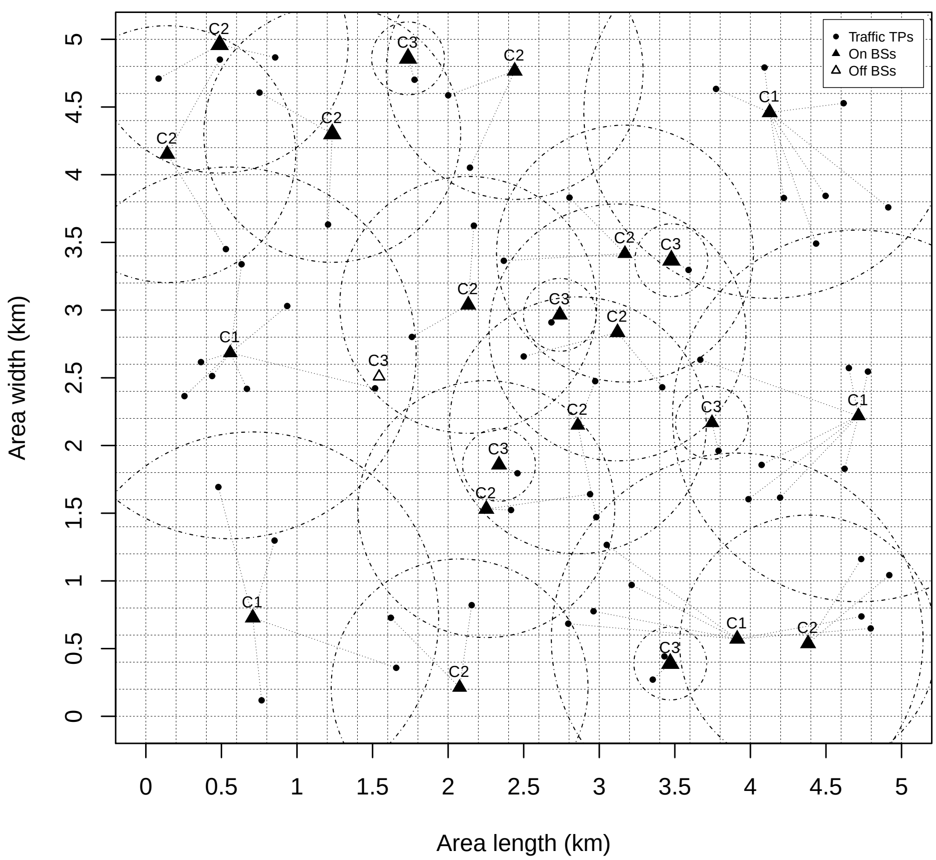

Figure 5.2 Scenario 2, $\beta = 0$ (two-step, total coverage), t_8: 22 BSs on out of 23.

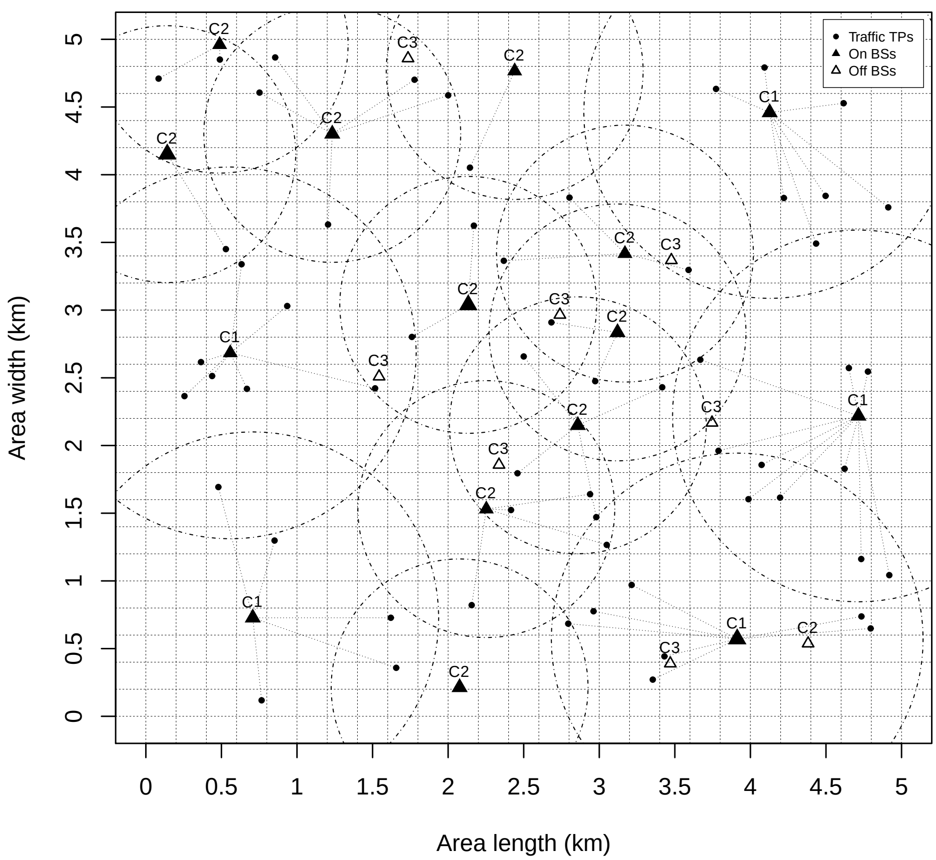

Figure 5.3 Scenario 2, $\beta = 0$ (two-step, total coverage), t_3: 15 BSs on out of 23.

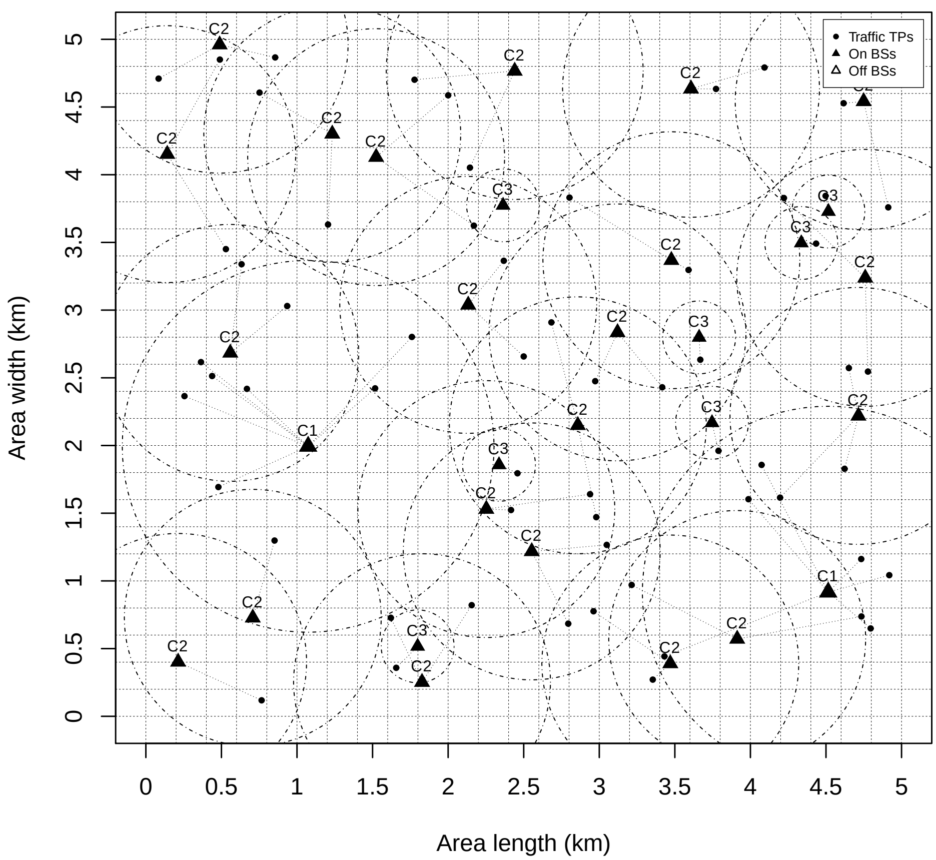

Figure 5.4 Scenario 2, $\beta = 1$ (joint, total coverage), t_8: 30 BSs on out of 30.

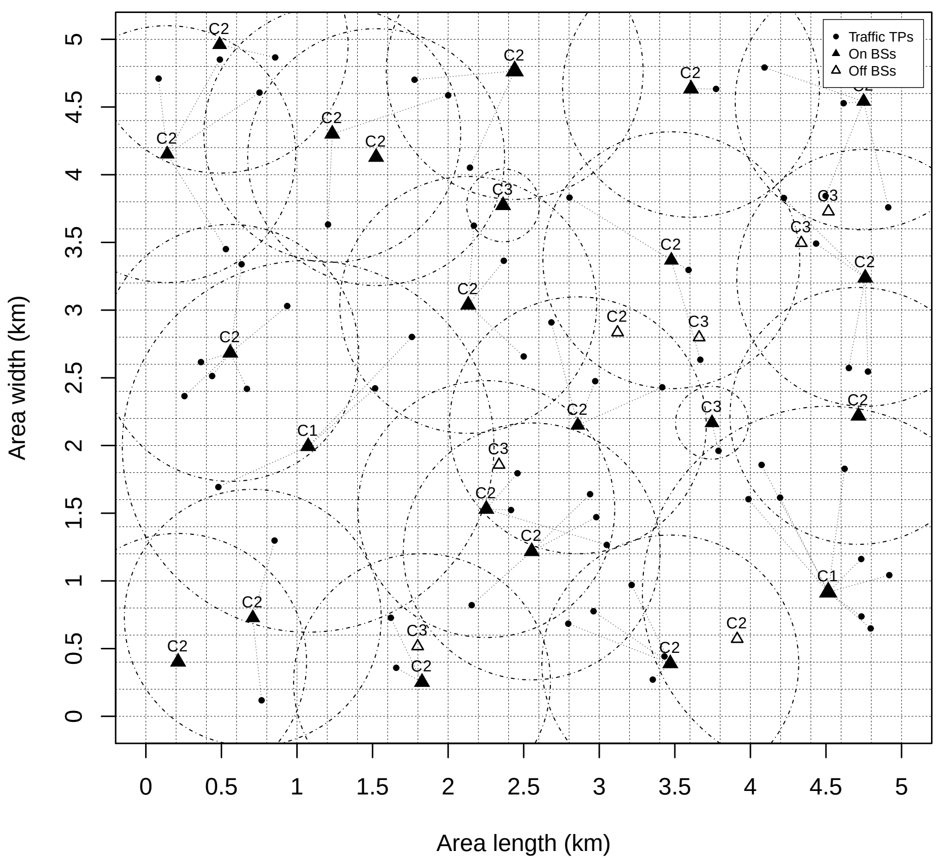

Figure 5.5 Scenario 2, $\beta = 1$ (joint, total coverage), t_3: 23 BSs on out of 30.

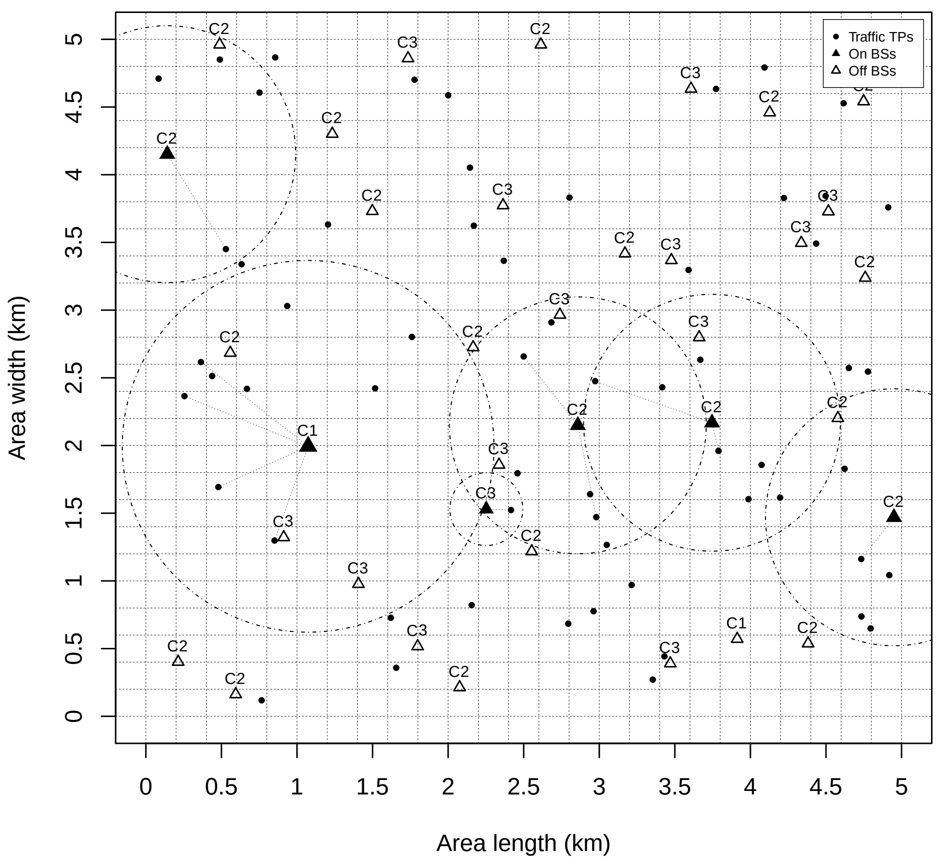

Figure 5.6 Scenario 2, $\beta = 1$ (joint, partial coverage), t_3: 6 BSs on out of 36.

deployed network, as soon as a TP switches from the idle to the active state, an additional BS can be turned on to route the new provided traffic. The outcome of the partial coverage approach, as called in Section 5.7.2, is displayed in Figure 5.6 for $\beta = 1$. Time period t_3 has been represented to point out the great difference with the previous examples: here we observe that only 6 BSs can serve the traffic requested by active users, but as much as 36 BSs are installed to ensure the area full coverage. Note that, to further increase the operational savings, the deployed network counts 6 more BSs than the topology obtained by using the joint approach with the same value of $\beta = 1$ (Figures 5.4 and 5.5). With reference to the joint optimization cases described above, where each TP had to lie in the coverage region of an active BS, 31% of energy savings ($\beta = 1$) are expected if the partial coverage approach is adopted, corresponding to almost 5250 € spared every year; moreover, the percentage raises to 61% when compared to the two-step total coverage approach depicted in Figure 5.2, which is equivalent to 13250 € yearly savings.

Tables 5.4 and 5.6 summarize the results obtained solving Scenario 2 with, respectively, the total and partial coverage models, using different values of the trade-off parameter β. Also, Tables 5.3 and 5.5 display the results for Scenario 1 in the same cases. The following entries are reported:

1. The resolution time required by CPLEX to optimize the test instances;
2. CapEx, expressed in Euro and corresponding to the value of the first component of the objective function;
3. OpEx for the whole network, calculated over a 8 year period by considering the Italian energy cost for business users of 0.35 € per kWh;
4. Number and type of BSs installed in the area;
5. Number of BSs powered on during every time period.

Percentages in parenthesis express the CapEx and energy consumption increase/decrease with respect to the case when $\beta = 0$ and only capital costs are minimized. Moreover, Tables 5.5 and 5.6 include percentage variations in CapEx and OpEx with respect to the corresponding examples in Table 5.3 and Table 5.4.

As already pointed out, increasing the value of β means increasing the installation costs as well as the number of BSs, while decreasing the total energy consumed. The same behavior can be observed for all test scenarios: taking as an example the results in Table 5.3, obtained for Scenario 1 by applying the original joint model, the CapEx growth turns out to be 11% with $\beta = 1$, 14% with $\beta = 5$ and 18% with $\beta = 10$ with respect to the two-step approach. Power demand, on the other hand, decreases 55% when $\beta = 1$, 57% when $\beta = 5$ and 60% when $\beta = 10$. With easy calculations, we found that when the trade-off parameter is set to 5, the

Table 5.3 Results obtained by applying the joint model with total coverage to Scenario 1.

	$\beta = 0$	$\beta = 0$ (two-step)	$\beta = 1$ (joint)	$\beta = 5$ (joint)	$\beta = 10$ (joint)
Time	44 *sec*	1 *sec* (oper)	25 *min* 11 *sec*	11 *min* 49 *sec*	11 *min* 1 *sec*
CapEx (k€)	56	56	62 *(+11%)*	64 *(+14%)*	66 *(+18%)*
OpEx (k€, 8 y, 0.35€/kWh)	42	39 *(-5%)*	19 *(-54%)*	18 *(-56%)*	17 *(-57%)*
Installed BSs	18	18	17	19	21
Configuration Types	C1 - 1	C1 - 1	C1 - 0	C1 - 0	C1 - 0
	C2 - 1	C2 - 1	C2 - 5	C2 - 5	C2 - 5
	C3 - 16	C3 - 16	C3 - 12	C3 - 14	C3 - 16
Turned On BSs	t_1 - 18	t_1 - 16	t_1 - 17	t_1 - 17	t_1 - 17
	t_2 - 18	t_2 - 9	t_2 - 10	t_2 - 10	t_2 - 10
	t_3 - 18	t_3 - 4	t_3 - 4	t_3 - 4	t_3 - 4
	t_4 - 18	t_4 - 8	t_4 - 10	t_4 - 10	t_3 - 11
	t_5 - 18	t_5 - 13	t_5 - 15	t_5 - 16	t_3 - 15
	t_6 - 18	t_6 - 14	t_6 - 15	t_6 - 16	t_3 - 15
	t_7 - 18	t_7 - 16	t_7 - 15	t_7 - 16	t_3 - 17
	t_8 - 18	t_8 - 17	t_8 - 17	t_8 - 17	t_3 - 18

extra capital investment, corresponding to 8000 €, can be retrieved in approximately 3 years from the savings in network operation, amounting to 2625 € per year. If we now consider the partial coverage variation and the same value of β, an additional 22% (corresponding to 4000 €, or 25000 € compared to the two-step results) can be saved in operational expenses at the cost of only 3% further increase in CapEx. Looking at tables 5.3 to 5.6, it is also worth underlining that, when β assumes values grater than 1, some deployed BSs are switched off not only during low traffic periods as t_3, but even when in maximum traffic, giving more importance to operation effectiveness with respect to capital savings.

Finally, we propose in Table 5.7 a comparison between the solutions achieved by applying the total and partial coverage joint models ($\beta = 1$) on Scenario 3 and its variations. As shown in Table 5.2, we created three alternative forms of Scenario 3, distinguished only by the fact that two out of three BS configurations can be installed: Scenario 3a allows configurations $C1$ and $C2$, Scenario 3b deploys only $C1$ and $C3$ while Scenario 3c admits configurations $C2$ and $C3$. By doing so, we try to demonstrate that flexibility is an essential network characteristic when the purpose is to guarantee an effective network operation, that is to say, maximizing the energy savings. As we can see from the table, Scenarios 3a and 3b behave poorly if compared to Scenario 3 and 3c: forbidding the installation of one of the two smaller configuration $C2$ and $C3$, the joint model is forced to deploy a higher number of bigger cells which, besides being expensive in terms of CapEx, consume a large amount of energy even when the total coverage is not required. So, for example, during time period t_8, 2 $C1$ BSs (in addition to 22 $C3$ BSs) are switched on in Scenario 3b when only active TPs have to be covered. On the other hand, observing Scenario 3, 4 $C2$ and 22 $C3$ cells are enough for

Table 5.4 Results obtained by applying the joint model with total coverage to Scenario 2.

	$\beta = 0$	$\beta = 0$ (two-step)	$\beta = 1$ (joint)	$\beta = 5$ (joint)	$\beta = 10$ (joint)
Time	25 *sec*	1 *sec* (oper)	1 *min* 51 *sec*	1 *min* 7 *sec*	19 *sec*
CapEx (k€)	267	267	277 *(+4%)*	298 *(+12%)*	299 *(+12%)*
OpEx (k€, 8 y, 0,35€/kWh)	203	198 *(-3%)*	134 *(-34%)*	115 *(-43%)*	115 *(-43%)*
Installed BSs	23	23	30	33	34
Configuration Types	C1 - 5	C1 - 5	C1 - 2	C1 - 2	C1 - 2
	C2 - 11	C2 - 11	C2 - 21	C2 - 23	C2 - 23
	C3 - 7	C3 - 7	C3 - 7	C3 - 8	C3 - 9
Turned On BSs	t_1 - 23	t_1 - 18	t_1 - 26	t_1 - 29	t_1 - 29
	t_2 - 23	t_2 - 14	t_2 - 22	t_2 - 23	t_2 - 22
	t_3 - 23	t_3 - 15	t_3 - 23	t_3 - 23	t_3 - 22
	t_4 - 23	t_4 - 14	t_4 - 22	t_4 - 23	t_4 - 22
	t_5 - 23	t_5 - 15	t_5 - 23	t_5 - 24	t_5 - 26
	t_6 - 23	t_6 - 18	t_6 - 27	t_6 - 29	t_6 - 30
	t_7 - 23	t_7 - 21	t_7 - 28	t_7 - 29	t_7 - 30
	t_8 - 23	t_8 - 22	t_8 - 30	t_8 - 30	t_8 - 31

Table 5.5 Results obtained by applying the joint model with partial coverage to Scenario 1.

	$\beta = 0$	$\beta = 0$ (two-step)	$\beta = 1$ (joint)	$\beta = 5$ (joint)	$\beta = 10$ (joint)
Time	27 *sec*	1 *sec* (oper)	28 *min* 28 *sec*	16 *min* 49 *sec*	22 *min* 12 *sec*
CapEx (k€)	56	56	62 *(+11%)*	66 *(+18%)*	66 *(+18%)*
Vs. Total Coverage	+0%	+0%	+0%	+3%	+0%
OpEx (k€, 8 y, 0.35€/kWh)	42	33 *(-21%)*	16 *(-62%)*	14 *(-67%)*	13 *(-69%)*
Vs. Total Coverage	-0%	-15%	-16%	-22%	-24%
Installed BSs	18	18	17	21	21
Configuration Types	C1 - 1	C1 - 1	C1 - 0	C1 - 0	C1 - 0
	C2 - 1	C2 - 1	C2 - 5	C2 - 5	C2 - 5
	C3 - 16	C3 - 16	C3 - 12	C3 - 16	C3 - 16
Turned On BSs	t_1 - 18	t_1 - 15	t_1 - 17	t_1 - 18	t_1 - 18
	t_2 - 18	t_2 - 7	t_2 - 11	t_2 - 12	t_2 - 12
	t_3 - 18	t_3 - 1	t_3 - 1	t_3 - 1	t_3 - 1
	t_4 - 18	t_4 - 7	t_4 - 11	t_4 - 11	t_4 - 11
	t_5 - 18	t_5 - 12	t_5 - 15	t_5 - 16	t_5 - 16
	t_6 - 18	t_6 - 13	t_6 - 14	t_6 - 15	t_6 - 15
	t_7 - 18	t_7 - 14	t_7 - 15	t_7 - 17	t_7 - 16
	t_8 - 18	t_8 - 16	t_8 - 17	t_8 - 19	t_8 - 19

Table 5.6 Results obtained by applying the joint model with partial coverage to Scenario 2.

	$\beta = 0$	$\beta = 0$ (two-step)	$\beta = 1$ (joint)	$\beta = 5$ (joint)	$\beta = 10$ (joint)
Time	16 *sec*	1 *sec* (oper)	2 *min* 20 *sec*	2 *min* 13 *sec*	2 *min* 47 *sec*
CapEx (k€)	267	267	274 *(+3%)*	340 *(+27%)*	362 *(+36%)*
Vs. Total Coverage	+0%	+0%	+1%	+14%	+21%
OpEx (k€, 8 y, 0.35€/kWh)	203	175 *(-13%)*	92 *(-54%)*	75 *(-63%)*	73 *(-64%)*
Vs. Total Coverage	-0%	-12%	-31%	-35%	-37%
Installed BSs	23	23	36	37	39
Configuration Types	C1 - 5	C1 - 5	C1 - 2	C1 - 3	C1 - 4
	C2 - 11	C2 - 11	C2 - 20	C2 - 24	C2 - 23
	C3 - 7	C3 - 7	C3 - 14	C3 - 10	C3 - 12
Turned On BSs	t_1 - 23	t_1 - 17	t_1 - 30	t_1 - 30	t_1 - 31
	t_2 - 23	t_2 - 12	t_2 - 17	t_2 - 18	t_2 - 19
	t_3 - 23	t_3 - 6	t_3 - 6	t_3 - 7	t_3 - 7
	t_4 - 23	t_4 - 9	t_4 - 15	t_4 - 14	t_4 - 14
	t_5 - 23	t_5 - 13	t_5 - 21	t_5 - 22	t_5 - 22
	t_6 - 23	t_6 - 15	t_6 - 23	t_6 - 29	t_6 - 29
	t_7 - 23	t_7 - 21	t_7 - 28	t_7 - 25	t_7 - 26
	t_8 - 23	t_8 - 22	t_8 - 32	t_8 - 29	t_8 - 30

Table 5.7 Significative results obtained applying joint model with total and partial coverage ($\beta = 1$) to Scenario 3 and its variations.

	Scenario 3	Scenario 3a	Scenario 3b	Scenario 3c
Total Coverage:				
CapEx (k€)	136	240 *(+76%)*	190 *(+40%)*	137 *(+0.7%)*
OpEx (k€, 8 y, 0.35€/kWh)	46	71 *(+54%)*	197 *(+328%)*	46 *(+0%)*
Installed BSs	C1 - 0	C1 - 0	C1 - 6	C1 - n.a.
	C2 - 12	C2 - 24	C2 - n.a.	C2 - 12
	C3 - 16	C3 - n.a.	C3 - 10	C3 - 17
Turned On BSs in t_3	C1 - 0	C1 - 0	C1 - 6	C1 - n.a.
	C2 - 12	C2 - 14	C2 - n.a.	C2 - 12
	C3 - 5	C3 - n.a.	C3 - 2	C3 - 5
Turned On BSs in t_8	C1 - 0	C1 - 0	C1 - 6	C1 - n.a.
	C2 - 12	C2 - 24	C2 - n.a.	C2 - 12
	C3 - 15	C3 - n.a.	C3 - 9	C3 - 17
Partial Coverage:				
CapEx (k€)	144	240 *(+67%)*	208 *(+44%)*	141 *(-2%)*
OpEx (k€, 8 y, 0.35€/kWh)	16	50 *(+213%)*	56 *(+250%)*	15 *(-6%)*
Installed BSs	C1 - 0	C1 - 0	C1 - 6	C1 - n.a.
	C2 - 12	C2 - 24	C2 - n.a.	C2 - 12
	C3 - 24	C3 - n.a.	C3 - 28	C3 - 21
Turned On BSs in t_3	C1 - 0	C1 - 0	C1 - 0	C1 - n.a.
	C2 - 2	C2 - 6	C2 - n.a.	C2 - 1
	C3 - 6	C3 - n.a.	C3 - 7	C3 - 6
Turned On BSs in t_8	C1 - 0	C1 - 0	C1 - 2	C1 - n.a.
	C2 - 4	C2 - 19	C2 - n.a.	C2 - 3
	C3 - 22	C3 - n.a.	C3 - 22	C3 - 20

serving the traffic provided by TPs in the busiest period, decreasing power consumption at almost one-fourth compared to the previous case. Similar results (but setting $\beta = 10$) are represented in Figures 5.9 and 5.10, while Figures 5.7 and 5.8 report the network topology obtained when the total area coverage is needed at all time.

5.8 Conclusion

Managing the network operation to follow traffic variations is certainly one of the most powerful instruments in mobile operator hands to reduce energy consumption, and so, operational costs. By proposing an optimization framework that selects the BSs to be installed and jointly switches them on and off according to the changing traffic load, in this paper we strove to demonstrate that for the power management to be truly effective networks have to be *designed* taking into account operational management.

The goal of our approach is not only to minimize both installation and operational costs, but also to find the best trade-off between keeping low initial investments and reducing energy consumption. Varying the trade-off parameter β between CapEx and OpEx, we got network topologies with different characteristics. Networks with a low installation cost are not very efficient from an energy consumption standpoint since those tend to use mostly big cells. On the other hand, the most energy efficient networks include not only small cells with low energy consumption, but also some bigger cells to provide the energy management mechanism with enough flexibility to adapt the network capacity in different time periods.

Future work will consider heuristic methods for very large scale network instances and the development of real-time on-line operation models incorporating user mobility.

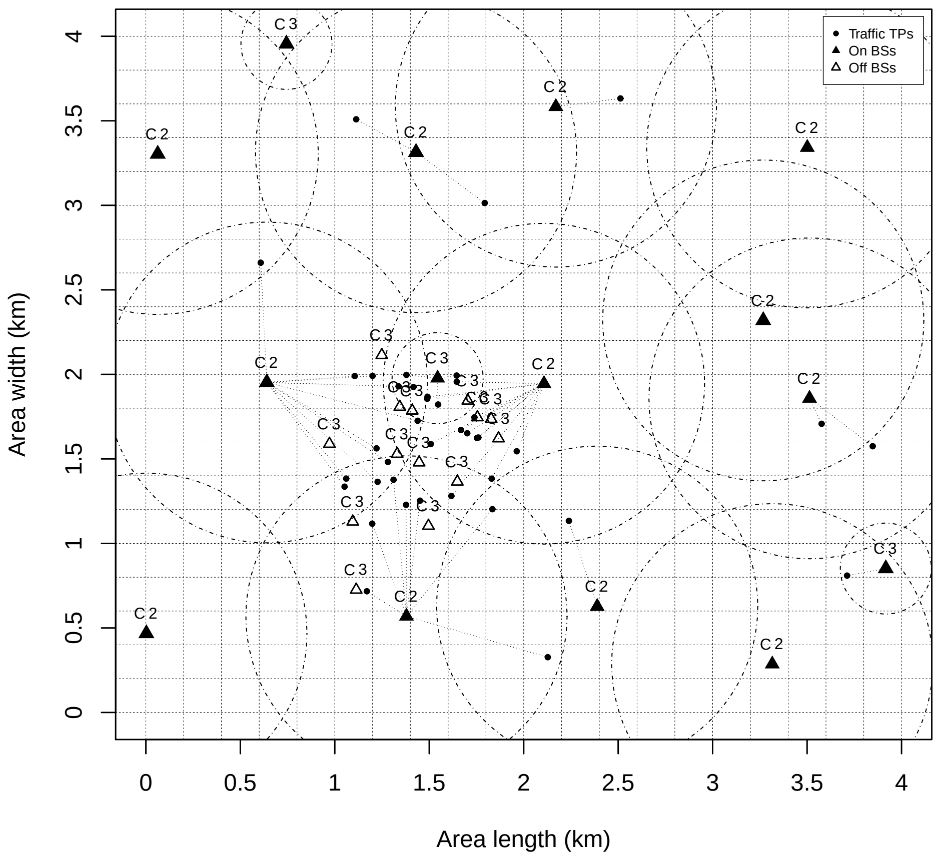

Figure 5.7 Scenario 3, $\beta = 10$ (joint, total coverage), t_3.

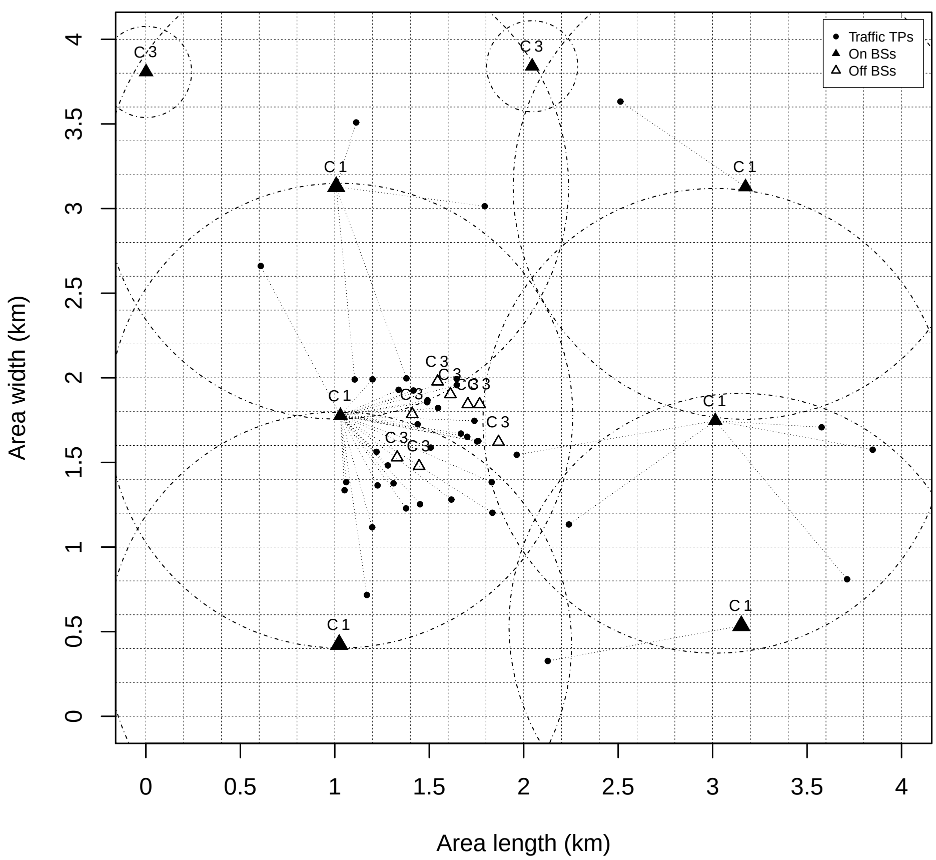

Figure 5.8 Scenario 3b, $\beta = 10$ (joint, total coverage), t_3.

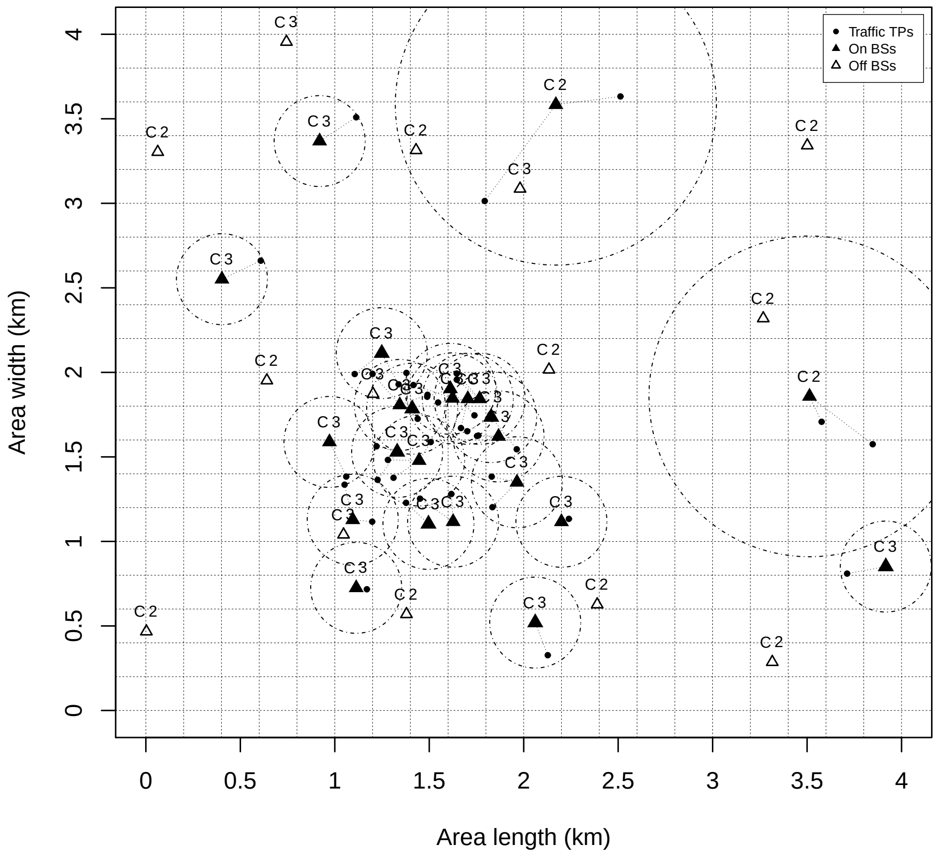

Figure 5.9 Scenario 3, $\beta = 10$ (joint, partial coverage), t_8.

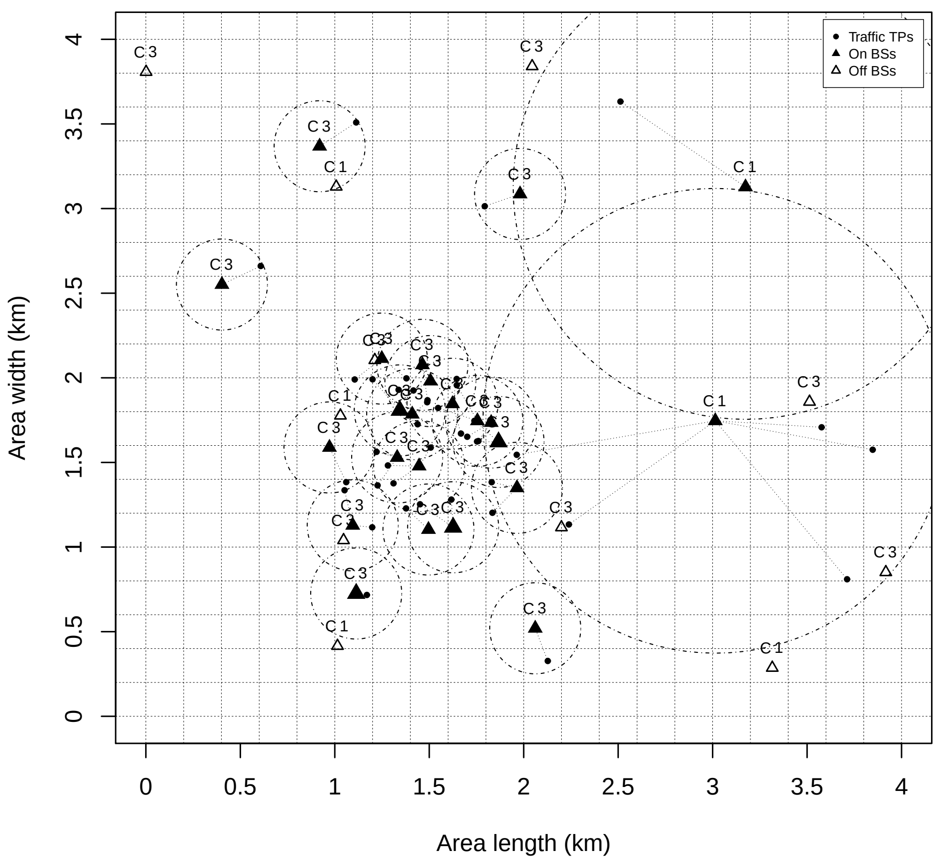

Figure 5.10 Scenario 3b, $\beta = 10$ (joint, partial coverage), t_8.

CHAPTER 6

ARTICLE 3: JOINT DESIGN AND MANAGEMENT OF ENERGY-AWARE MESH NETWORKS

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6.1 Abstract

This paper deals with the joint planning and energy management operation of wireless mesh networks. We claim that energy management should be incorporated at the planning stages to produce an effective energy-management operation. For this, we propose a mathematical framework that takes into account the trade-off of capital expenditures versus energy-related operational ones when designing the network. We also present results that put into relevance the impact of different coverage policies on energy efficiency.

6.2 Introduction

The debate on global warming and energy efficiency in ICT is becoming increasingly important. There is now evidence (The Climate Group, 2008), that the ICT industry has a significant part of responsibility for the global carbon emissions, with telecommunications networks (including mobile, WLANs, LANs and wired networks) representing almost 50% of ICT power expenditures (Koutitas and Demestichas, 2010).

The answer of the research community has been *green networking*, consisting on a new way of building and managing telecommunications networks to reduce their energy needs. As a matter of fact, it is clear that working towards the so-called green networks is not only profitable in terms of the cost savings related to power expenses (*OpEx*, operational and management expenditures), but also allows the deployment of networks having low environmental impact.

Among the network segments, the access is the one with the major influence on energy consumption, being liable for 80% of the overall power expenditures (Gruber *et al.*, 2009; Koutitas and Demestichas, 2010). This is mostly because WANs (WANs) are usually dimensioned to satisfy the quality constraints under peak traffic conditions, resulting in over-provisioning in low-demand periods thus wasting a significant amount of power. From this point of view, trying to minimize the energy consumption of deployed access elements (that is to say, base stationss) is an important goal.

There has been interesting models and approaches to deal with the problem of power savings in both wireless and wired networks (Mellah and Sansò, 2009). Nevertheless, a fundamental issue that has been overlooked is that an effective energy-aware operation is closely dependent on the *planning* decisions taken during the network design phase. In other words, we claim that when the network is designed with the classical cost-performance trade-off, the energy management operation would be less efficient than if energy management is directly incorporated at the planning stages. To the best of our knowledge, the only example of this kind of analysis can be found in our previous work Boiardi *et al.* (2010), where the significant advantages of jointly optimizing network design and operation in cellular networks are evaluated.

Differently from Boiardi *et al.* (2010), we focus here on wireless mesh networks (WMNs), a newly emerged type of access network offering wireless connectivity with the use of cheap and low transmission power devices. WMNs are dynamically self-organized and self-configured communication infrastructures, with a high degree of cooperation between many individual wireless stations. Each node works not only as a host but also as a router, forwarding packets on behalf of other nodes that may not be within direct transmission range of their destinations. Thus, the nodes automatically establish mesh connectivity among themselves, creating in effect an ad hoc network (Akyildiz *et al.*, 2005). However, as usually happens in the other types of access networks, WMNs infrastructure devices are always active. Thus, during lower traffic periods the energy consumption is the same as in busy hours, while it would be possible to save a large amount of power by turning off unnecessary nodes. Concerning this issue, an energy-aware approach for such kind of networks was tackled in Capone *et al.* (2012b), where the power expenses of a deployed network were minimized by dynamically selecting a subset of base stationss to be switched on. However, that article did not consider energy management jointly with network planning but as a purely operational feature.

The question that we want to answer in this paper is, given the highly adaptive features of mesh networks, to what extend the philosophy of jointly planning and energy optimization yields important energy efficient results. For this, we will proceed to present a mathematical framework and extensive results to seize the advantage of this type of approach for Wireless Mesh green networking.

The reminder of the paper is structured as follows. In Section 6.3 we present an overview on related work. Section 6.4 provides a description of the Wireless Mesh system and gives an overview of planning and operational models that are important preliminaries to understand the joint optimization framework that is presented in Section 6.5. The resolution approach is presented in Section 6.6, where we also explain the model variations used for testing the effectiveness of our optimization method. Numerical results are fully commented in Section 6.7, while Section 6.8 concludes the paper.

6.3 Related work

Several studies on green networking have appeared in the last few years, starting from the seminal work of Gupta and Singh (2003). A complete overview of the main research ideas on this topic can be found in Minami and Morikawa (2008) and Mellah and Sansò (2009), where the authors survey different proposals for reducing the power consumption in both wired and wireless networks.

Despite the fact that wireless systems have high responsibility in the increase of power expenditures, most of the work on infrastructure consumption have focused on wired networks. However, wireless research has always been involved in energy-related problems given the mobile nature of the network devices that is pushing for improvements in batteries life and coverage techniques. Therefore, the literature includes many studies on energy-efficient *devices* (Zhang *et al.*, 2006; Louhi, 2007) and *protocols* (Jones *et al.*, 2001) for WLANs and cellular networks (for an excellent review, see Karl *et al.* (2003)). On the other hand, the interest in infrastructure wireless green networking design and operation has only started in recent years and deals more with *management* than with planning issues.

For instance, concerning WLANs, in Jardosh *et al.* (2007) and Jardosh *et al.* (2009) the resource on demand (RoD) approach is proposed, aiming at powering off some access points during off-peak traffic periods following real-time traffic variations or fixed pre-determined schedules. The system behavior under two different RoD strategies is evaluated in Marsan *et al.* (2010). Considering cellular networks, several works assess the possibility of switching off some nodes when they are underutilized, based on average measurements of traffic exchange between nodes (Chiaraviglio *et al.*, 2008b) or deterministic traffic variations during the day (Marsan *et al.*, 2009). In our previous work Boiardi *et al.* (2010), for the first time the energy expenses problem is tackled from a dual standpoint: given that an effective energy-aware network operation closely depends on the locations chosen for the network devices, we develop a joint design and management model that aims at limiting both energy consumption and operational expenditures.

Concerning WMNs in general, previous work concentrates mainly on MAC and routing protocols, mobility management and security topics. Most of the time, the network topology (that is to say, the positions of routers and gateways) was pre-established and the goal was to optimize the routing or the channel assignment. Few authors have investigated the problem of planning wireless mesh access networks. In Wang *et al.* (2007), a single pre-installed access point is considered and only the positions of routers are optimized, while in Qiu *et al.* (2004) and He *et al.* (2007) the authors formulate a modeling approach for locating gateways given the locations of the other nodes. A mathematical model for the complete WMN design is proposed in Amaldi *et al.* (2008), where the number and positions of mesh routers and access points are to be selected, always taking into account typical network issues such as traffic routing and channel assignment. In the context of green networking, an energy-aware management for WMNs is obtained in Capone *et al.* (2012b) where starting from a previously deployed network, the authors try to minimize the power consumption in a time varying context by dynamically turning on and off some base stations (routers or access points) (see Section 6.4.3 for more details on the models presented in Amaldi *et al.*, 2008; Capone *et al.*, 2012b).

A very interesting framework is presented in Chen *et al.* (2011) where four fundamental trade-offs for an effective green network are stated and an excellent overview of the current and future studies in green networking research area is presented. Moreover, the exhaustive analysis of the Deployment Efficiency - Energy Efficiency (DE-EE) trade-off reported in Chen and Tsai (2010) is a good starting point to better understand the importance and complexity of the issue we tackle in this paper.

Differently from the aforementioned papers, we present the following original contributions:

- We propose the joint optimization of the planning and energy-aware operation for wireless mesh networks and create, for the first time, a rigorous optimization model.
- We compare the savings obtained with the joint planning and operation framework philosophy with the one obtained when planning and energy aware operation are performed in separate stages.
- We compare the energy savings obtained for Mesh and cellular networks obtained with the same type of modeling philosophy.
- We study the effect of different planning and operating coverage strategies on overall network consumption.

6.4 System description and preliminary mathematical models

The philosophy of the modeling framework that will be presented in Section 6.5 is based on exploiting the dynamic features of WMNs to design a system that is not only cost-effective, but also follows the demand in an energy-efficient way during normal operation.

In order to follow the demand, we must first characterize it by time periods and the energy management framework will consist in deciding which device should be put down during the daily operation to minimize energy consumption. As the model is jointly a planning and an operational one, the framework idea is to choose, at the same time, the network configuration and the operational features.

In the rest of this Section, we first provide an overview of the WMN system description. Next, we discuss how traffic variations are characterized. The last subsection is devoted to revisiting the planning and operational models that have been previously presented and that are necessary to understand our joint planning and operation proposal of Section 6.5.

6.4.1 System description

wireless mesh networks are made up of two types of fixed elements, mesh routers (MRs) and mesh access points (MAPs), forming the mesh backbone for mobile users, named mesh clients (MCs). From now on, when generally referring to MRs and MAPs the term base stations (BSs) will be used. Both kinds of BSs have the task of setting up a wireless distribution system (WDS) by connecting to other mesh routers and access points through point to point wireless links while providing network access for the MCs. In addition, MAPs, representing only a restricted set of routers, behave as gateways toward the wired backbone, enabling the integration of WMNs with other networks (typically the Internet).

In developing our WDS, we follow the assumptions made in Capone *et al.* (2012b). MRs and MAPs that reside in the respective covering ray can communicate through dedicated wireless channels, each one having bidirectional capacity unvarying with the distance. We admit that the traffic in a link does not affect closer links since all devices are equipped with multiple network interfaces. Concerning MCs, they can be assigned to a BS only if they are included in a circular cell centered in the BS and having a ray of $250\,m$. Moreover, mesh users are served by the nearest active router and are connected to the Internet through multi-hop communications.

In terms of numerical values, we use the Wi-Fi 802.11n standard for communication between routing devices, with a nominal link capacity of $450\,Mbps$ and a coverage ray of $450\,m$. Note that the coverage ray between two BSs is almost doubled with respect to the one between BSs and MCs since directive antennas are used for connecting MRs and MAPs in order to limit unwanted interference. Finally, the access technology Wi-Fi 802.11g with $54\,Mbps$ is chosen, shared among all users assigned to a BS.

6.4.2 Traffic variations pattern

Different studies have dealt with traffic variations measurement in wireless access networks (Pries *et al.*, 2009; Heegaard, 2007). Considering an approximated traffic profile based on these studies, in Lorincz *et al.* (2010); Boiardi *et al.* (2010); Capone *et al.* (2012b) the authors split the whole day into time periods in order to take into account the demand fluctuations in WLANs, cellular or mesh networks, respectively. By dividing the day into smaller intervals in which users behavior is assumed unchanged, the on-off operation of the access network will allow following the traffic variations and reducing power consumption of unneeded devices.

Let T be the ordered set of time periods displayed in Table 6.1. Note that no time gap is admitted between adjacent intervals, and the summed duration of all intervals is equal to the number of hours in a day. A value ρ_t is assigned to each time period, representing the probability that an MC provides traffic to the network. In other words, ρ_t is the *percentage of active users* typical of every time interval.

As presented in Capone *et al.* (2012b), two different degrees of congestion have been tested:

- *Standard profile*, in which active MCs provide a traffic amount randomly generated between 1 and 10 $Mbps$;
- *Busy profile*, in which the demand of active users varies from 8 to 10 $Mbps$.

6.4.3 Basic approaches to network planning and energy management

Before introducing our joint network design and management model (in Section 6.5) we briefly present the two mathematical programming models representing the basic approaches to the separate problems of WMN planning (Amaldi *et al.*, 2008) and WMN energy management (Capone *et al.*, 2012b). Note that the original notation was changed for commonality in model description.

WMN planning

The general idea of the formulation presented in Amaldi *et al.* (2008) is deciding where and what kind of access devices should be installed in order to satisfy the users demand and minimize CapEx costs. Let S be the set of candidate sites (CSs) available to host a MR or a MAP and let I be the set of MCs, each one providing a constant traffic value defined by $d_i, i \in I$. Let N be a special node representing the Internet. Moreover, the set $J_h^{(i)}$ is required to recognize the most convenient BSs for every MCs: it represents the subset of BSs covering user i, ordered by decreasing received power.

Table 6.1 Time periods and demand variations during a day.

Index	1	2	3	4	5	6	7	8
Start	00:00	3:00	6:00	9:00	12:00	15:00	18:00	21:00
End	3:00	6:00	9:00	12:00	15:00	18:00	21:00	24:00
Duration	3 h	3 h	3 h	3 h	3 h	3 h	3 h	3 h
ρ_t	0.35	0.1	0.45	1	0.7	0.85	0.6	0.5

Two are the required binary parameters: a_{ij} is equal to 1 if MC i is covered by the BS located in site j, while b_{jl} is equal to 1 if a wireless link can be installed between the BSs in sites j and l.

The binary decision variables x_{ij} are used to assign MC i to the BS located in j, the installation variables z_j indicate wether CS j is chosen in the solution, variables w_j show if a MAP is installed in site j and variables k_{jl} define if the BSs located in j and l are connected through a wireless link. Additional integer variables f_{jl} represent the traffic on wireless link (j, l), while f_{jN} is the flow from the MAP in site j to the Internet.

The mathematical model of the WMN design problem is the following:

$$\min \quad \sum_{j \in S} (z_j \gamma_j + p_j w_j) \tag{6.1}$$

$$\text{subject to:} \quad \sum_{j \in S} x_{ij} = 1 \qquad \forall i \in I \tag{6.2}$$

$$x_{ij} \leq a_{ij} z_j \qquad \forall i \in I, j \in S \tag{6.3}$$

$$\sum_{l \in S} (f_{lj} - f_{jl}) + \sum_{i \in I} d_i x_{ij} = f_{jN} \qquad \forall j \in S \tag{6.4}$$

$$f_{lj} + f_{jl} \leq u_{jl} k_{jl} \qquad \forall j, l \in S \tag{6.5}$$

$$f_{jN} \leq m w_j \qquad \forall j \in S \tag{6.6}$$

$$\sum_{i \in I} x_{ij} d_i \leq c_j \qquad \forall j \in S \tag{6.7}$$

$$k_{jl} \leq z_j, \quad k_{jl} \leq z_l \qquad \forall j, l \in S \tag{6.8}$$

$$k_{jl} \leq b_{jl} \qquad \forall j, l \in S \tag{6.9}$$

$$z_{J_l^{(i)}} + \sum_{h=l+1}^{l_i} x_{iJ_l^{(i)}} \leq 1 \qquad \forall i \in I, l : 1 \ldots B_i - 1 \tag{6.10}$$

$$x_{ij},\ z_j,\ k_{jl},\ w_j \in \{0, 1\} \qquad \forall i \in I, j, l \in S \tag{6.11}$$

Objective function (6.1) minimizes the network deployment costs, given by a basic installation cost γ_j common to all BSs located and additional costs p_j due to the connection of MAPs to the Internet. Constraints (6.2) and (6.3) insure that each MC is assigned to a BS that covers it. (6.4) are flow balance equations, while (6.5), (6.6) and (6.7) are capacity constraints for links, MRs and MAPs respectively. Constraints (6.8) and (6.9) guarantee that a link is installed only if the two involved nodes are both active and neighbors, while (6.10) force the assignment of every MC to the nearest installed BS. Finally, constraints (6.11) impose binary values for some decision variables.

Notably, this formulation does not take into account any network operation or energetic aspect and no demand variations over time are considered. These will be taken into account in the next subsection.

WMN energy management

The model revisited here was formulated in Capone *et al.* (2012b). Given an existing network, the problem is that of deciding which BSs should be switched off according to the variations of the users traffic profiles. In addition to the two sets previously defined, let T be the set of time intervals described in Table 6.1 and let $G \subseteq S$ the subset of BSs that are MAPs.

Since the traffic offered by users is different depending on the time intervals, an extended traffic matrix d_{it} is defined. The assignment of MCs can now change in time, so that decision variables x, f and f_N are now identified by one more index t. Another group of variables, y_{jt}, is introduced to indicate if the BS located in j is active at time t.

The WMNs energy management formulation is the following:

$$\min \quad \sum_{j \in S} \sum_{t \in T} \epsilon_j z_{jt} \Delta(t) \tag{6.12}$$

$$\text{subject to:} \quad \sum_{j \in S} x_{ijt} = 1 \qquad \forall i \in I, t \in T \tag{6.13}$$

$$x_{ijt} \leq a_{ij} z_{jt} \qquad \forall i \in I, j \in S, t \in T \tag{6.14}$$

$$\sum_{l \in S} (f_{ljt} - f_{jlt}) + \sum_{i \in I} d_{it} x_{ijt} = f_{jNt} \qquad \forall j \in S, t \in T \tag{6.15}$$

$$f_{ljt} + f_{jlt} \leq u_{jl} b_{jl} z_{jt} \qquad \forall j, l \in S, t \in T \tag{6.16}$$

$$f_{jNt} \leq m \qquad \forall j \in S, t \in T \tag{6.17}$$

$$\sum_{i \in I} x_{ij} d_i \leq c_j \qquad \forall j \in S, t \in T \tag{6.18}$$

$$z_{J_l^{(i)}} + \sum_{h=l+1}^{l_i} x_{iJ_l^{(i)}} \leq 1 \qquad \forall i \in I, l : 1...B_i - 1 \tag{6.19}$$

$$x_{ij},\ z_j \in \{0, 1\} \qquad \forall i \in I, j, l \in S \tag{6.20}$$

Here the objective function (6.12) aims at minimizing the sum of BSs energy consumption ϵ_j over all time periods. As for the previously described model, (6.13) and (6.14) are assignment constraints, (6.15) are flow balance constraints and (6.16), (6.17) and (6.18) are capacity constraints for links, MAPs Internet access and BSs. Finally, constraints (6.19) guarantee the best possible assignment for every user. Constraints (6.20) impose binary values to the decision variables.

6.5 Joint network design and management for Wireless Mesh Networks

In the previous Section, we revisited, respectively, a planning and energy management model for WMNs. In this Section, we present a joint planning and management optimization approach based on the modeling philosophy proposed in Boiardi *et al.* (2010) for cellular networks that combines the minimization of installation costs and the maximization of energy savings. This way we strive to underline the tight relationship existing between an effective energy-aware network operation and wise decisions made during planning phases. We now present the notational framework, a reference model as well as some key relaxations that will be used for comparison purposes in the results section.

6.5.1 Notational framework

To be able to set the mathematical model, we need an additional notation. For the sake of completeness, some of the notation that was first presented in Section 6.4.3 is also included here.

Sets

I : Set of MCs generating variable traffic;
S : Set of the available CSs for the BSs;
T : Set of time intervals;
$J_h^{(i)}$: Subset of BSs covering MC i, ordered by descending received power.

Parameters

d_{it} : Traffic provided by MC i in period t;
c_j : Access capacity of the BS located in site j;
u_{jl} : Capacity of the wireless link between BSs located in sites j and l;
m : Capacity of the MAPs Internet access;
γ_j : Installation cost for a MR located in site j;

p_j : Installation cost for a MAP located in site j (it includes the cost for connecting the MAP with the wired backbone);

ϵ_j : Power consumption for a MR located in site j;

ψj : Power consumption for a MAP located in site j;

B_i : Number of BSs covering MC i;

$\Delta(t)$: Duration of time period t;

β : Weight parameter used for trading-off the objective function.

a_{ij} : Equal to 1 if MC i is covered by a BS installed in j, 0 otherwise;

b_{jl} : Equal to 1 if a wireless link between BSs located in sites j and l is possible, 0 otherwise.

Variables

$$z_j = \begin{cases} 1 & \text{if a MR is installed in site } j, \\ 0 & \text{otherwise;} \end{cases} \tag{6.21}$$

$$w_j = \begin{cases} 1 & \text{if a MAP is installed in site } j, \\ 0 & \text{otherwise;} \end{cases} \tag{6.22}$$

$$y_{jt} = \begin{cases} 1 & \text{if the MR installed in site } j \text{ is active in period } t, \\ 0 & \text{otherwise;} \end{cases} \tag{6.23}$$

$$r_{jt} = \begin{cases} 1 & \text{if the MAP installed in site } j \text{ is active in period } t, \\ 0 & \text{otherwise;} \end{cases} \tag{6.24}$$

$$x_{ijt} = \begin{cases} 1 & \text{if MC } i \text{ is assigned to a BS installed in site } j \\ & \text{ in period } t, \\ 0 & \text{otherwise;} \end{cases} \tag{6.25}$$

$$k_{jl} = \begin{cases} 1 & \text{if there is a wireless link between the BSs in} \\ & \text{sites } j \text{ and } l, \\ 0 & \text{otherwise;} \end{cases} \tag{6.26}$$

f_{jlt} : Flow between BSs located in sites j and l in time t;

f_{jNt} : Flow between MAP located in site j and Internet (N) in time t.

6.5.2 The reference model

The first joint network design and management problem for WMNs will be called $(P0)$ and it is defined as follows:

The objective function

$$\min \quad \beta \sum_{j\in S}(z_j\gamma_j + p_j w_j) + (1-\beta)\sum_{j\in S}\sum_{t\in T}(\epsilon_j y_{jt} + \psi_j r_{jt})\Delta(t) \tag{6.27}$$

The objective function is composed of two terms. The first one represents the installation costs of MRs and MAPs in selected CSs (CapEx), while the second one accounts for the power consumption of the active devices in any time interval (OpEx). The parameter β, which varies in the $[0,1]$ interval, represents the trade-off between the two components, as it changes the importance given to the OpEx with respect to the CapEx. Starting from $\beta = 1$, when just capital expenses are minimized, we will gradually reach the opposite case of $\beta = 0$ (minimization of power costs only) after evaluating individual values. Then, comparing the intermediate results with the two extreme cases, we will be able to underline the benefits of our approach and show how both network planning and management can be wisely improved by considering them in a joint fashion.

Assignment constraints

$$\sum_{j\in S} x_{ijt} = 1 \qquad \forall i \in I, t\in T \tag{6.28}$$

$$x_{ijt} \leq a_{ij}(y_{jt} + r_{jt}) \qquad \forall i \in I, j\in S, t \in T \tag{6.29}$$

Two different assignment constraints are needed. Equations (6.28) impose that every MC is assigned to one and only one BS. Constraints (6.29) assign every MC only to a BS that is active and that covers it.

Installation constraints

$$z_j + w_j \leq 1 \qquad \forall j \in S \tag{6.30}$$

Installation constraints (6.30) guarantee that at most one device (MR or MAP) is installed in every CS.

Activation constraints

$$y_{jt} \leq z_j \qquad \forall j \in S, t \in T \tag{6.31}$$

$$r_{jt} \leq w_j \qquad \forall j \in S, t \in T \tag{6.32}$$

These constraints allow the activation of a MR (6.31) or a MAP (6.32) in any time period only if the device has been installed.

Flow conservation constraints

$$\sum_{l \in S}(f_{ljt} - f_{jlt}) + \sum_{i \in I} d_{it}x_{ijt} = f_{jNt} \qquad \forall j \in S, t \in T \tag{6.33}$$

Constraints (6.33) define the flow balance in site j. The term $\sum_{l \in S} f_{ljt}$ is the total traffic received by j from neighboring sites, $\sum_{l \in S} f_{jlt}$ is the total traffic transmitted by j to neighboring sites, $\sum_{l \in i} d_{it}x_{ijt}$ is the traffic related to the users assigned to j and f_{jNt} is the traffic transmitted to the wired backbone.

Capacity constraints

$$\sum_{i \in I} x_{ijt}d_{it} \leq c_j(y_{jt} + r_{jt}) \qquad \forall j \in S, t \in T \tag{6.34}$$

$$f_{ljt} + f_{jlt} \leq u_{jl}k_{jl} \qquad \forall j, l \in S, t \in T \tag{6.35}$$

There are two different groups of capacity constraints. (6.34) insures that the total traffic demand of the MCs assigned to a BS does not exceed the BS capacity, while constraints (6.35) refer to the maximum capacity available for existing links.

Link use constraints

$$f_{ljt} + f_{jlt} \leq u_{jl}(y_{jt} + r_{jt}) \qquad \forall j, l \in S, t \in T \tag{6.36}$$

$$f_{ljt} + f_{jlt} \leq u_{jl}(y_{lt} + r_{lt}) \qquad \forall j, l \in S, t \in T \tag{6.37}$$

$$f_{jNt} \leq m r_{jt} \qquad \forall j \in S, t \in T \tag{6.38}$$

Constraints (6.36) and (6.37) allow the use of the link (l, j) only in the case BSs in j and l are turned on. Equations (6.38) state that the capacity of the MAPs Internet access must not exceed m, while forcing the flow toward the backbone to zero if the device in j is not a gateway.

Link existence constraints

$$k_{jl} \leq z_j + w_j \qquad \forall j, l \in S \tag{6.39}$$

$$k_{jl} \leq z_l + w_l \qquad \forall j, l \in S \tag{6.40}$$

$$k_{jl} \leq b_{jl} \qquad \forall j, l \in S \tag{6.41}$$

The three constraints above allow the existence of a wireless link between two BSs only if they are both active ((6.39) and (6.40)) and neighbors (6.41).

Best power constraints

$$y_{J_l^{(i)}t} + r_{J_l^{(i)}t} + \sum_{h=l+1}^{l_i} x_{iJ_l^{(i)}t} \leq 1 \qquad \forall i \in I, t \in T, l : 1...B_i - 1 \tag{6.42}$$

Constraints (6.42) force the assignment of every MC to the most convenient BS, according to a proper parameter such as the received signal strength.

Binary constraints

$$x_{ijt} \in \{0, 1\} \qquad \forall i \in I, j \in S, t \in T \tag{6.43}$$

$$y_{jt}, r_{jt} \in \{0, 1\} \qquad \forall j \in S, t \in T \tag{6.44}$$

$$z_j, w_j \in \{0, 1\} \qquad \forall j \in S \tag{6.45}$$

$$k_{jl} \in \{0, 1\} \qquad \forall j, l \in S \tag{6.46}$$

Finally, binary constraints impose binary values to some of the decision variables.

6.5.3 The partial covering-relaxed problem

In order to underline the importance of our study and compare the results in different situations, we have also developed a relaxed variation of the reference model. Just like ($P0$), the *Partial Covering-Relaxed Problem* ($P1$) aims at providing a full-coverage network deployment, but in this case our objective is that of guaranteeing network services only to those clients that are active in any time period: in this way, those BSs that have only inactive users in their covering ray can be turned off.

For this purpose, we need to introduce a new set of binary parameters h_{it} that is equal to 1 if the MC i is providing traffic in time period t. Then, in order to limit the network service only to active users, constraints (6.28) of $(P0)$ should be replaced by:

$$h_{it}x_{ijt} \leq a_{ij}(y_{jt} + r_{jt}) \qquad \forall i \in I, j \in S, t \in T \tag{6.47}$$

$(P1)$ can then be written as:

$$\begin{aligned} \min \quad & (6.27) \\ \text{subject to:} \quad & (6.28), (6.47), (6.30) - (6.46). \end{aligned}$$

6.6 Resolution approach

The proposed mathematical model has been developed using the AMPL programming language and optimized with the CPLEX solver.

Realistic mesh network instances have been generated modifying the IG proposed in Capone *et al.* (2012b). The main features of the IG are given below.

6.6.1 Instance Generator and input assumptions

Since our model generates a network topology and manages network operation, the main task of the IG is to randomly place CSs and users location in the analyzed area. Also, for each client, the instance generator computes two random traffic values in each time interval, according to the different congestion levels presented in Section 6.4.2. Then, for every pair of MC and CS, it computes the mutual distance and sets the corresponding value of a_{ij} to 1 if user i is in the coverage ray of the BS that could be installed in j. The same operation is done for each couple of CSs, in order to verify if a wireless link is possible between them and set the corresponding parameters b_{jl} to the correct values.

In order to produce factual mesh network instances, some IG input parameters referring to BSs features and derived from real field tests were set to the following values:

- Covering ray for communications between BSs: $450\,m$;
- Covering ray for communications between a BS and a MC: $250\,m$;
- Capacity u_{jl} of the wireless link connecting two BSs located in j and l, $\forall j, l \in S$: $300\,Mb/s$;
- Capacity m of MAPs Internet access: $10\,Gb/s$;

- Access capacity c_j for a BS located in $j, \forall j \in S$: $40\,Mb/s$;
- Installation cost γ_j for a MR located in $j, \forall j \in S$: 200 €;
- Installation cost p_j for a MAP located in $j, \forall j \in S$: 400 €;
- Power consumption ϵ_j for a MR located in $j, \forall j \in S$: $15\,W$;
- Power consumption ψ_j for a MAP located in $j, \forall j \in S$: $18\,W$.

Moreover, specific control parameters are added to the random generation to guarantee the network feasibility. Also note that in our tests,we assume that the power consumed by MRs and MAPs do not vary with link utilization, which, depending on the type of equipment, may be a reasonable assumption.

6.6.2 Test scenarios

With the help of the IG three different WMN test scenarios were generated. Their features are described in Table 6.2. The first column reports the name that will be used to identify the instance. The second entry represents the area size (expressed in squared meters) and the next is the number of CSs available in the area. The last column presents the number of users placed in the area.

As introduced in Section 6.4.2, we considered two different traffic profiles for every test scenario. In both situations, during time period t only a percentage ρ_t of users provides traffic to the network. When the *standard profile* is considered, the traffic value related to each MC is randomly chosen by the IG between 1 and $10\,Mb/s$, while the same value ranges from 8 to $10\,Mb/s$ in the case of *busy profile*.

6.6.3 Additional tests and variations

To underline the effectiveness of our results, we introduce three other possible variations of the problem.

Variable capacity for backbone wireless links

As reported in subsection 6.6.1, in our tests we use a fixed capacity u_{ij} of 300 Mb/s for wireless links connecting two BSs, provided that they are no more than 450 m away. In order

Table 6.2 Characteristics of the WMN test scenarios.

WMN Size	Area Size (m^2)	CSs Number	MCs Number
Small	1000×1000	16	60
Medium	1500×1500	40	130
Large	2500×2500	64	240

to verify the soundness of our assumption, we have also created a set of experience that sets different values of link capacity depending on the BSs mutual distance:

- Distance up to 60 m from BS i to BS j: $u_{ij} = 300Mb/s$;
- Distance 60 m—120 m from BS i to BS j: $u_{ij} = 240Mb/s$;
- Distance 120 m—200 m from BS i to BS j: $u_{ij} = 180Mb/s$;
- Distance 200 m—300 m from BS i to BS j: $u_{ij} = 120Mb/s$;
- Distance 300 m—450 m from BS i to BS j: $u_{ij} = 60Mb/s$.

Thus, our purpose is to demonstrate that no substantial variation in CapEx and OpEx values, as well as in the network design and management, appears when the fixed capacity assumption is adopted.

The cellular comparison

Here we assume that no router can be installed so that each CS can host only a gateway (MAP). This case represents a *cellular network* where every base station behaves as a gateway, being directly connected to the backbone and routing the traffic towards the Internet without the help of other nodes. This *MAPs only* scenario aims at sizing the energy savings that can be obtained if a multi-hop mesh network is deployed instead of a cellular one.

The two-step approach

In the third test, the energy management model proposed in Capone *et al.* (2012b) and reported in Section 6.4.3 is applied to a pre-computed network design. Differently from the network planning considered in Capone *et al.* (2012b), this is directly obtained from the model we propose by setting the weight parameter β to 1, so it is optimized to get the minimum capital expenses. This kind of approach can be identified as a *two-step* approach, since the network design is computed first and only then an energy management model can be applied to the network. Thus, by comparing our joint model results with the ones given by the *two-step* optimization, we strive to show the effects of a combined approach on the network deployment and the benefits on energy savings.

The relaxed two-step approach

Finally, we test a different version of the *two-step* procedure described above where the energy management is executed by considering only the active MCs. In this last case, the model presented in Section 6.4.3 is modified by excluding constraints (6.14) and setting the value of the summation in constraints (6.13) equal to h_{it}. We refer to Capone *et al.* (2012b) for more details on the adopted relaxing technique. This *relaxed two-step* approach will be compared with the results obtained by our problem $(P1)$.

6.7 Numerical results

In this Section, we present selected results from a large set of instances for Problems $(P0)$, $(P1)$ and its variations.

6.7.1 Savings obtained using the reference model

This subsection is devoted to the presentation of summary results as well as more detailed results concerning the application of the basic planning and operation problem $(P0)$.

Summary results

For every scenario, we tested different values of β to see the effect of giving more weight to the operational and energetic aspect of the network.

Table 6.3 provides an overview of the percentage of energy savings that can be obtained by exploiting the joint design and management model $(P0)$. Each entry refers to a particular value of β applied to the previously described test scenarios . The percentages are calculated with respect to the energy requirement of the same test scenarios when β is set to 1. In fact, when $\beta = 1$ no energy saving operational considerations are taken into account and the model provides a simple network design optimization. As a result, all the installed BSs are constantly turned on and no energy management mechanism is enabled.

One can observe from the values in the table that by just setting β to 0.8, which enables the energy management term of the objective function, the energy consumption during the day decreases by more than 30% in the best situations. These reductions are due to the fact that, when the weight parameter is smaller than 1, our joint approach is pushed to optimize not only the topology but also the operation of the considered network. Therefore, only those BSs that are required for routing the MCs' traffic or guaranteeing the total area coverage are

Table 6.3 Comparison of energy saving percentages obtained from $(P0)$ in all test scenarios (percentages are referred to the cases of $\beta = 1$).

	Small Standard	Small Busy	Medium Standard	Medium Busy	Large Standard	Large Busy
$\beta = 0.8$	20.49%	29.32%	12.39%	32.11%	17.94%	25.51%
$\beta = 0.5$	27.66%	29.32%	14.98%	32.11%	20.80%	28.01%
$\beta = 0.1$	27.66%	30.09%	20.87%	32.67%	23.11%	28.84%

turned on, while the others can be powered off. Further decreases of β lead to low decreases of the energy consumption in the *busy* version of all the test scenarios, while better results come from the cases with standard traffic. This difference in the network behavior is clearly caused by a higher amount of traffic that has to be managed in the *busy* profile cases.

Detailed results

Some detailed results on energy efficiency, costs and energy management can be found in Table 6.4, that shows more clearly how $(P0)$ behaves when applied to the largest test scenario. The rows of the table display, respectively, the values of capital expenditures (CapEx, expressed in Euro), the energy requirements during the day (expressed in Wh), the daily energy expenses (expressed in Euro and based on the Italian energy cost for business users of 0.2 €/kWhour) and the number of installed routers (MRs) and gateways (MAPs). The percentages in parenthesis show the savings with respect to the case with $\beta = 1$. Every column, except for the second one (that will be explained in the next subsection), gathers the results obtained with different values of β. One can see how the energy savings increase as β decreases, how the planning is different (different number of installed MRs and MAPs) and how the operation changes.

The same trend can be observed in Figure 6.1 where the scenario was chosen since it was the easiest to appreciate from the visual point of view. Every subfigure represents the network configuration obtained with a certain value of β and shows its behavior in a given time period. In particular, the lowest- and the highest-traffic time intervals (t_2 and t_4) are analyzed. Black triangles and squares symbolize active MRs and MAPs respectively, while MRs and MAPs that are installed but inactive are represented by the same white symbols. All the MCs are depicted as black dots, but only the MCs providing traffic are connected by dotted lines to the BS they are assigned to. However, since $(P0)$ guarantees the total network coverage, every MC resides at least in one BS coverage area, represented in the pictures by a dotted circumference centered in each active BS location. Finally, the network structure is revealed by black lines linking MRs and MAPs for routing the traffic received from the clients towards the Internet.

If $\beta = 1$, only CapEx costs are minimized (Figures 6.1a and 6.1b), no energy management is enabled and all the installed BSs are active during the whole day. Even when only 6 MCs are active (t_2), so much as 11 MRs are turned on: they are useful for providing the network coverage but, on the other hand, the great overlap between the coverage areas would allow to turn off some of them. This is what happens when $\beta < 1$. As an example, in Figures 6.1c and 6.1d the solution obtained for $\beta = 0.5$ is displayed. Now, only those MRs that are really required for serving active MCs or providing network coverage are turned on (7

Table 6.4 Size “large”, Traffic “standard”. Summary of the results from ($P0$) with different values of β and comparison with *two-step* approach.

	$\beta = 1$	**two-step**	$\beta = 0.5$	$\beta = 0.1$
CapEx (€)	9600	9600	10000	12400
Energy (Wh/day)	16704	15264 ***(-8.62%)***	13230 *(-20.80%)*	12843 ***(-23.11%)***
OpEx (€/day, 0.2 €/kWh)	3.34	3.05	2.65	2.57
Installed MRs	44	44	46	50
Installed MAPs	2	2	2	6
Turned On MRs - MAPs	t_1 - 44 - 2	t_1 - 40 - 2	t_1 - 31 - 2	t_1 - 28 - 4
	t_2 - 44 - 2	t_2 - 39 - 2	t_2 - 31 - 2	t_2 - 29 - 3
	t_3 - 44 - 2	t_3 - 40 - 2	t_3 - 33 - 2	t_3 - 30 - 5
	t_4 - 44 - 2	t_4 - 43 - 2	t_4 - 44 - 1	t_4 - 39 - 4
	t_5 - 44 - 2	t_5 - 39 - 2	t_5 - 34 - 2	t_5 - 30 - 4
	t_6 - 44 - 2	t_6 - 41 - 2	t_6 - 39 - 2	t_6 - 35 - 4
	t_7 - 44 - 2	t_7 - 39 - 2	t_7 - 32 - 2	t_7 - 28 - 4
	t_8 - 44 - 2	t_8 - 39 - 2	t_8 - 32 - 2	t_8 - 28 - 4

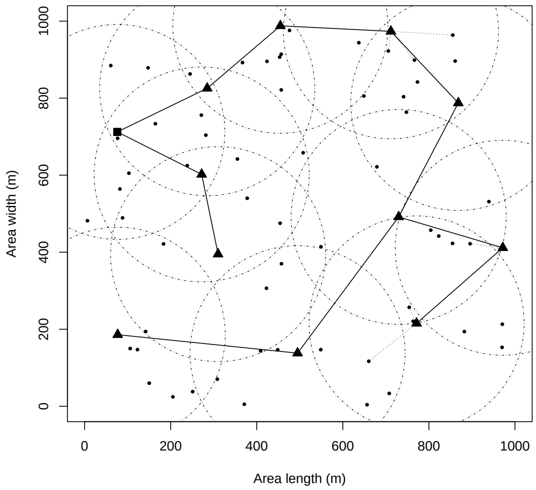
in time period 2, 10 in time period 4). Therefore, thanks to the role played by the power management mechanism, energy savings of 21.5% with respect to the previous case can be reached for the analyzed scenario. Also note that when the value of β decreases, the network design changes in order to find the best trade-off between CapEx and OpEx savings.

Comparison with the case of variable backbone links capacity

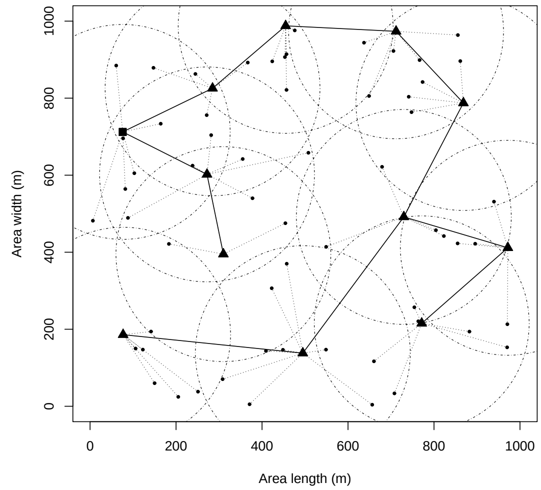
Figure 6.2 presents some network configurations obtained by letting the backbone links capacity vary with the distance between the BSs. Given that the displayed test scenario, the values of β and the selected time periods are the same of Figure 6.1, one can easily compare the pictures in order to focus on the differences caused by the capacity variation..

Looking at the cases of $\beta = 1$ we note that, in both Figure 6.1 (fixed link capacty) and Figure 6.2 (variable link capacity), 11 MRs and 1 MAP are constantly turned on, which indicates that CapEx and OpEx costs are the same. Now, even though OpEx expenditures do not vary in Figure 6.2b (representing the highest-traffic time period) more backbone links are activated due to their reduced capacity.

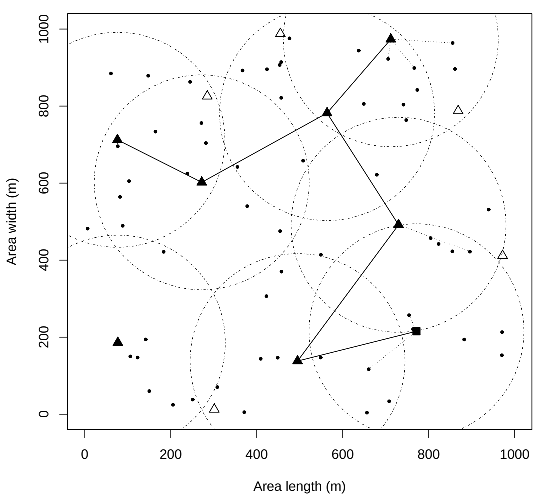
Another difference is shown in Figures 6.2c and 6.2d, representing the network configurations when $\beta = 0.5$. We observe that in the variable capacity case one more MAP is deployed and switched on in place of a MR, allowing the traffic to be routed through two different access points. This way, a lower number of links and particularly routers has to be installed: 10 MRs and 2 MAPs compared to 12 MRs and 1 MAP installed in the original example. Accordingly, we observe a slight increase (+3.68%) in OpEx due to the MAPs higher operational cost, while no additional CapEx expenses are required.



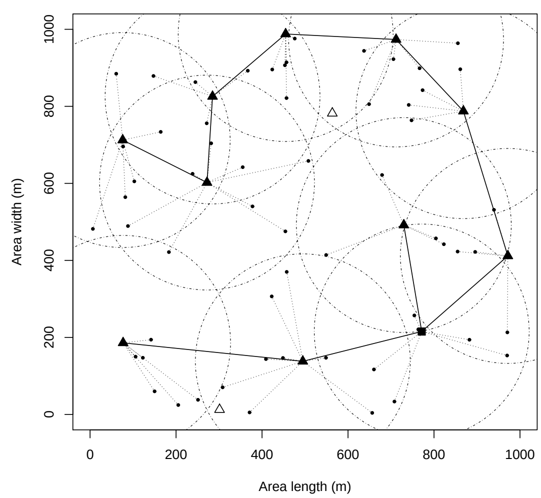
(a) $\beta = 1$, t_2: *11 MRs, 1 MAP.*



(b) $\beta = 1$, t_4: *11 MRs, 1 MAP.*

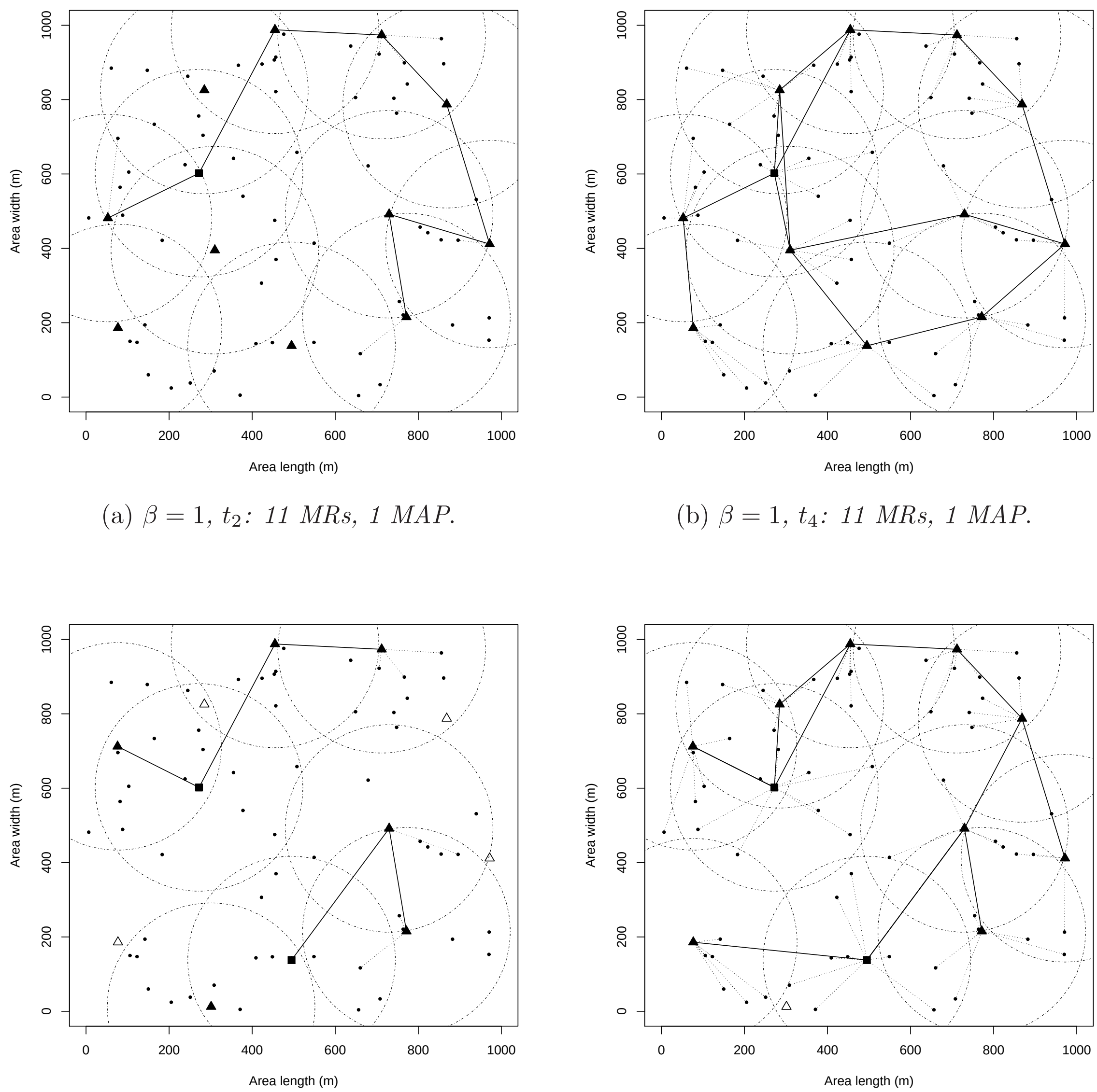


(c) $\beta = 0.5$, t_2: *7 MRs, 1 MAP.*



(d) $\beta = 0.5$, t_4: *10 MRs, 1 MAP.*

Figure 6.1 ($P0$): "Small" scenario, "Standard" traffic. Network design and behavior for different values of β.



(a) $\beta = 1$, t_2: *11 MRs, 1 MAP.*

(b) $\beta = 1$, t_4: *11 MRs, 1 MAP.*

(c) $\beta = 0.5$, t_2: *6 MRs, 2 MAP.*

(d) $\beta = 0.5$, t_4: *9 MRs, 2 MAP.*

Figure 6.2 ($P0$): "Small" scenario, "Standard" traffic, variable backbone links capacity. Network design and behavior for different values of β.

Comparison with the two-step procedure

An important point that we wanted to evaluate is what is the level of savings provided by the joint optimization when compared with the optimal energy operation of a well designed network. To be fair, we optimized first the planning by using $(P0)$ with $\beta = 1$, and next we introduced the resulting network into an optimal operation model, such as the one given in Capone *et al.* (2012b). The results are provided in the tables in the column titled "two-step". Note that in this case, since the two optimization problems are independent, it is not possible to adjust the importance of the energy issue with respect to the installation cost according to particular network needs. Such a regulation can be done exclusively by applying the joint design and management approach, where the network planning and management are handled at the same time and tuned by a proper weight parameter.

Observing first the numbers obtained for $\beta = 1$ and then the ones corresponding to lower values of β, it is clear that by enabling the power management mechanism good energy saving can be achieved. In particular, our joint approach produces savings that are not limited to the minimum cost topology, but it trades off between the two terms of the objective function to reach the best compromise of energy saving and installation cost reduction. For example, if $\beta = 0.5$ we more than double the energy savings given by the *two-step* approach at the cost of a modest increase (+4.17%) in CapEx expenses. Similarly, by investing the 29.17% more in the installation phase, energy savings of almost 24% are possible for $\beta = 0.1$.

It must be noticed that, despite the fact that CapEx increases could seem higher than energy savings, the latter spread during the whole period of operation, while network operators meet capital investments only once. Taking the case of $\beta = 0.5$ as an example, one can estimate that the additional initial investments, corresponding to 400 €, can be recovered from the energy saving in less than two years of network operation (259.15 €/year spared), which is a short period compared to the average network life.

Cellular comparison

In Table 6.5 the same "large" scenario is considered, but in this case the *MAPs only* approach is applied. Such an approach "mimics" the case of a purely cellular network. Thus, the idea of this comparison is to determine the levels of energy savings provided by the flexibility of mesh networks. Back to Table 6.5, we present in bold the percentage increases in CapEx and energy expenditures with respect to the values in Table 6.4. Clearly, since only the most expensive and energy hungry devices can be deployed and that there is no flexibility related to mesh networking, both capital investments and power expenditures face a sensible

Table 6.5 Size "large", Traffic "standard", *MAPs only* approach. Summary of the results with different values of β.

	$\beta = 1$	$\beta = 0.5$	$\beta = 0.1$
CapEx (€)	18000	18800	21600
Capex Diff. - vs ($P0$)	**+87.50%**	**+88.00%**	**+74.19%**
Energy (Wh/day)	19440	15876 *(-18.33%)*	15120 *(-22.22%)*
Energy Diff - vs ($P0$)	**+16.38%**	**+20.00%**	**+17.73%**
OpEx (€/day, 0.2 €/kWh)	3.89	3.18	3.02
Installed MAPs	45	47	54
Turned On MAPs	t_1 - 45	t_1 - 34	t_1 - 33
	t_2 - 45	t_2 - 33	t_2 - 31
	t_3 - 45	t_3 - 36	t_3 - 35
	t_4 - 45	t_4 - 44	t_4 - 44
	t_5 - 45	t_5 - 37	t_5 - 34
	t_6 - 45	t_6 - 41	t_6 - 39
	t_7 - 45	t_7 - 34	t_7 - 32
	t_8 - 45	t_8 - 35	t_8 - 32

increase. Despite that, our joint approach applied to the cellular case still insures energy savings of 18% for $\beta = 0.5$ with 4.44% extra CapEx and more than 22% for $\beta = 0.1$.

6.7.2 Savings obtained using the partial covering-relaxed model

Tables 6.6 and 6.7 show the results computed for the smallest scenario with respectively standard and busy traffic profile for the partial covering-relaxed problem ($P1$). The Tables show capital expenditures, the amount of energy and its cost in a day and the number of installed gateways and routers. Moreover, energy decrease percentages obtained by comparing the results with the ones of ($P0$) for the same scenario are reported. The column "relax two-step" refers to the last model variation described in Section 6.6.3 which, starting from a given complete coverage topology, manages the network so as to provide services only to the active users. In this case, the energy decrease percentage is related to the value of energy found by the *two-step* approach rather than the one of ($P0$). Also, in order to illustrate the behavior of the energy management mechanism we also report the number of MRs and MAPs switched on in every time interval.

As already noticed, by jointly optimizing installation and operation costs we can obtain high energy savings. Significant is the case of $\beta = 0.5$: if one more MR is installed at the modest extra cost of 200 €, power consumption will be reduced by almost 22%. Formulation ($P1$) shows the same behavior of ($P0$) but, compared to the latter, ($P1$) can reduce the energy expenditures of a percentage in the 9% to 15% range. This appears straightforward, since the network service must be guaranteed only for the users providing traffic, while BSs

Table 6.6 Size “small”, Traffic “standard”. Summary of the results from $(P1)$ with different values of β and comparison with *relaxed two-step* approach.

	$\beta = 1$	**relax two-step**	$\beta = 0.5$	$\beta = 0.1$
CapEx (€)	2600	2600	2800	3400
Energy (Wh/day)	3762	3267 ***(-15.18%)***	2952 *(-21.53%)*	2727 ***(-27.51%)***
OpEx (€/day, 0.2 €/kWh)	0.75	0.65	0.59	0.55
Energy Diff. - vs $(P0)$	-14.34%	-6.44% (vs *2-step*)	-7.08%	-12.93%
Installed MRs - MAPs	11 - 1	11 - 1	12 - 1	11 - 3
Turned On MRs - MAPs	t_1 - 9 - 1	t_1 - 7 - 1	t_1 - 6 - 1	t_1 - 4 - 2
	t_2 - 5 - 1	t_2 - 5 - 1	t_2 - 4 - 1	t_2 - 0 - 3
	t_3 - 10 - 1	t_3 - 8 - 1	t_3 - 6 - 1	t_3 - 4 - 2
	t_4 - 11 - 1	t_4 - 10 - 1	t_4 - 10 - 1	t_4 - 8 - 3
	t_5 - 10 - 1	t_5 - 9 - 1	t_5 - 7 - 1	t_5 - 7 - 1
	t_6 - 10 - 1	t_6 - 9 - 1	t_6 - 9 - 1	t_6 - 5 - 3
	t_7 - 10 - 1	t_7 - 8 - 1	t_7 - 7 - 1	t_7 - 6 - 2
	t_8 - 9 - 1	t_8 - 7 - 1	t_8 - 7 - 1	t_8 - 5 - 2

Table 6.7 Size “small”, Traffic “busy”. Summary of the results from $(P1)$ with different values of β and comparison with *relaxed two-step* approach.

	$\beta = 1$	**relax two-step**	$\beta = 0.5$	$\beta = 0.1$
CapEx (€)	3400	3400	3400	3600
Energy (Wh/day)	4572	3717 ***(-18.70%)***	3672 *(-19.69%)*	3654 ***(-20.087%)***
OpEx (€/day, 0.2 €/KWh)	0.91	0.74	0.73	0.73
Energy Diff. - vs $(P0)$	-21.60%	-9.83% (vs *2-step*)	-10.92%	-10.38%
Installed MRs - MAPs	15 - 1	15 - 1	15 - 1	14 - 2
Turned On MRs - MAPs	t_1 - 8 - 1	t_1 - 6 - 1	t_1 - 6 - 1	t_1 - 6 - 1
	t_2 - 10 - 1	t_2 - 2 - 1	t_2 - 2 - 1	t_2 - 0 - 2
	t_3 - 10 - 1	t_3 - 7 - 1	t_3 - 7 - 1	t_3 - 7 - 1
	t_4 - 15 - 1	t_4 - 15 - 1	t_4 - 15 - 1	t_4 - 14 - 2
	t_5 - 13 - 1	t_5 - 13 - 1	t_5 - 12 - 1	t_5 - 12 - 1
	t_6 - 14 - 1	t_6 - 13 - 1	t_6 - 13 - 1	t_6 - 12 - 2
	t_7 - 12 - 1	t_7 - 9 - 1	t_7 - 9 - 1	t_7 - 9 - 1
	t_8 - 10 - 1	t_8 - 8 - 1	t_8 - 8 - 1	t_8 - 8 - 1

covering only idle users can be powered off. Looking now at the last part of the table, one can notice how the network devices are managed in order to minimize the total power consumption. During lower-traffic periods (intervals 1 and 2), 9 or 5 MRs over 11 are turned on when $\beta = 1$: the management mechanism is not able to power off other BSs due to the small covering ray of wireless mesh devices. On the other hand, the highest number or routers is used when the traffic presents its peak. Decreasing the value of β and focusing in particular on $\beta = 0.1$, we observe a smaller number of active BSs in all time intervals (even 0 routers in period 2), while a higher number of MAPs is installed and turned on in order to better manage the traffic of the MCs. The results described above are represented in Figure 6.3. On the left side, the solutions obtained for $\beta = 1$, 0.5 and 0.1 in time period 2 are displayed, while solutions for time period 4 are on the right side.

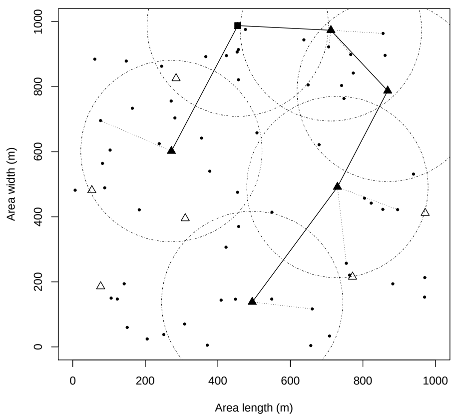
For the sake of completeness, we report in Table 6.7 the results we found for the "small" scenario where active users provide an amount of traffic between 8 and 10 $Mbps$, what we call the "busy" scenario. Compared to the ones in Table 6.6, the power savings are lower as was expected given that we get less flexibility when there is more demand. Nevertheless the approach still manages to get percentage of savings around 20% for both $\beta = 0.5$ and $\beta = 0.1$.

Finally, in Figure 6.4 we summarize the percentage variations of capital and energy expenses obtained by applying ($P0$) (Figure 6.4a) and ($P1$) (Figure 6.4b) to the three "standard" traffic test scenarios. Each point in the graphs corresponds to the percentage increment of CapEx and decrement of energy costs, with respect to the case of $\beta = 1$, obtained by playing with the weight parameter.

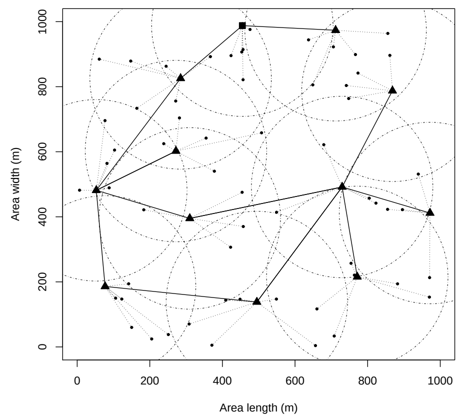
6.8 Conclusion

In this paper we have tackled the problem of designing energy-aware wireless mesh networks. Starting from the key idea that a wise network management is probably the best way to save power and reduce operational expenses, we have developed an optimization framework that selects the devices to be installed and jointly considers their dynamic energy-aware operation. Therefore, the objective of this optimization approach is that of minimizing at the same time capital and operational expenses, which are mostly due to energy consumption.

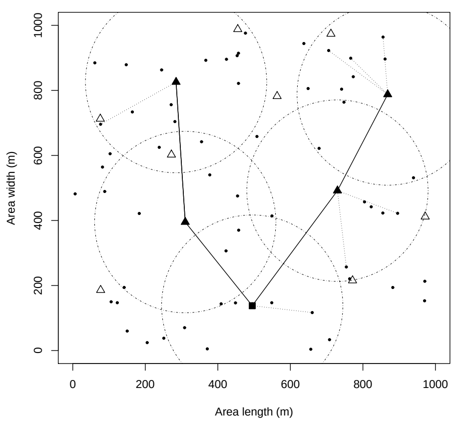
By mean of three test scenarios and several additional model variations, we have shown that an optimal network topology from the installation cost point of view does not produce a network that is optimal for an energy-aware operation and that it is necessary to plan ahead with the use of the joint planning and operational tool. In particular, varying the trade-off parameter β between CapEx and OpEx, we have found that important energy



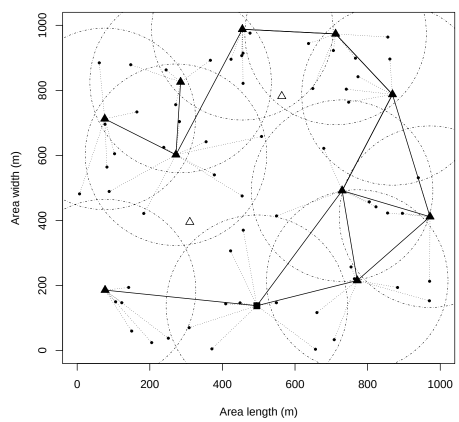
(a) $\beta = 1$, t_2*: 5 MRs, 1 MAP.*



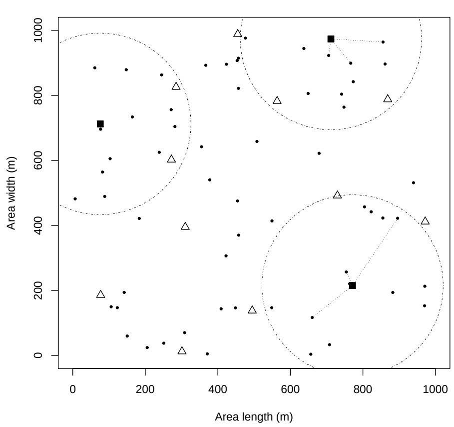
(b) $\beta = 1$, t_4*: 11 MRs, 1 MAP.*



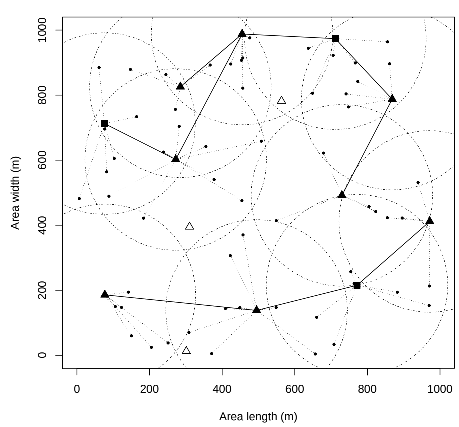
(c) $\beta = 0.5$, t_2*: 4 MRs, 1 MAP.*



(d) $\beta = 0.5$, t_4*: 10 MRs, 1 MAP.*

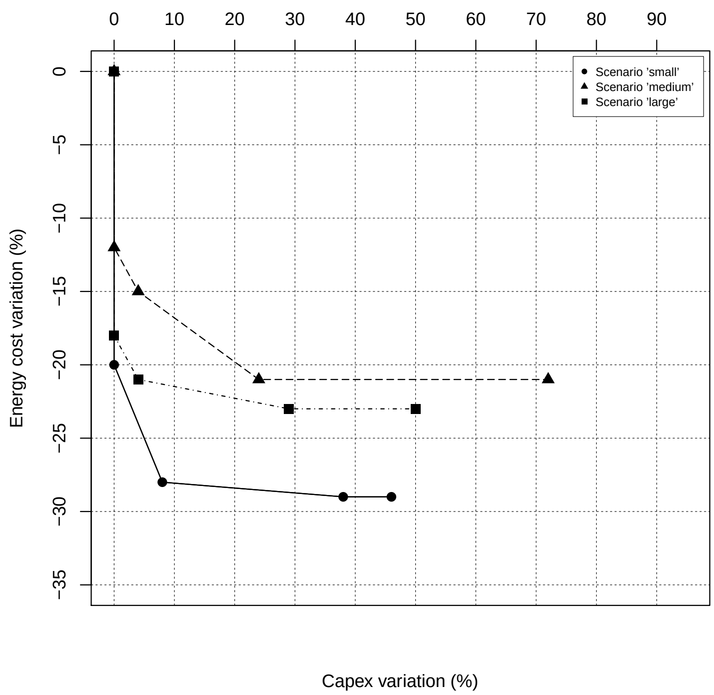


(e) $\beta = 0.1$, t_2*: 0 MRs, 3 MAPs.*

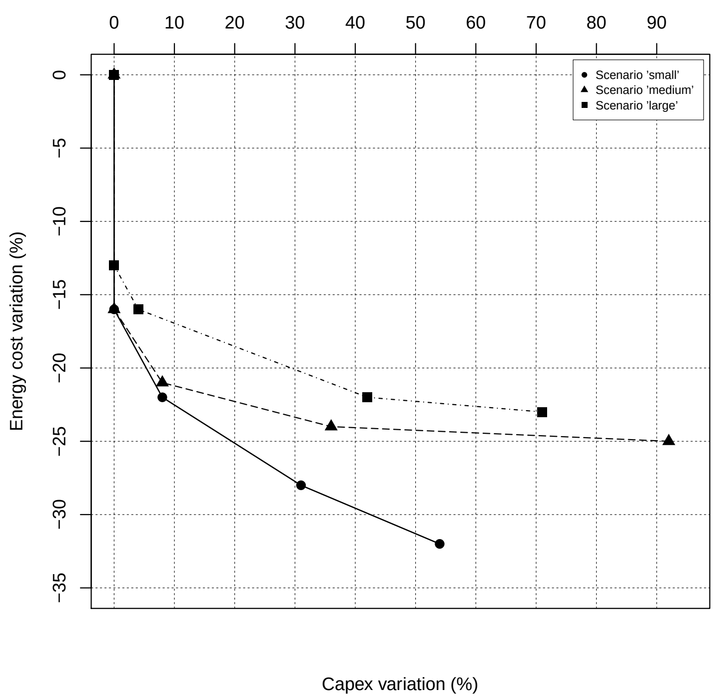


(f) $\beta = 0.1$, t_4*: 8 MRs, 3 MAPs.*

Figure 6.3 ($P1$), "Small" scenario, "Standard" traffic. Network design and behavior for different values of β.



(a) $(P0)$, *"standard" traffic.*



(b) $(P1)$, *"standard" traffic.*

Figure 6.4 Capital and energy expenses variations for different values of β.

savings can be reached at the cost of little increases in installation investments. Moreover, the effectiveness of our framework has been confirmed by comparing our results with the ones obtained from a more “traditional” two-step approach, where network planning and energy-aware operation are optimized separately. The joint framework was also applied to a cellular architecture, showing that it still produces good energy savings results but that they are less important than those obtained with mesh networking. Finally, we evaluated the effect of partial covering in the procedure and found that more than ten percent energy savings can still be achieved when some coverage constraints are relaxed, regardless of the case, which shows the importance of a more flexible wireless network coverage control for energy savings.

CHAPTER 7

ADDITIONAL MODEL VARIATIONS

7.1 Introduction

In addition to the journal papers constituting Chapters 4, 5 and 6, other articles have been produced and presented in international conferences throughout the doctoral research. Paper Boiardi *et al.* (2012c), accepted at the 21^{st} International Conference on Computer Communications and Networks (ICCCN), summarizes the same concepts that have been extensively explained in Chapter 5, providing preliminary results for the joint planning and energy management problem for cellular networks (JPEM-CN) LTE technology. Illustrating the early stages of the JPEM framework applied to cellular networks, the paper does not include supplementary original contents. However, an unpublished variation of the framework for cellular networks have been developed, which simplify the JPEM-CN objective function by introducing a new set of constraints to limit the CapEx. Similarly, a modified version of the joint planning and energy management problem for wireless mesh networks (JPEM-WMN) described in Chapter 6 is shown in Boiardi *et al.* (2012a), included in the proceeding of the 10^{th} IEEE global communications conference (Globecom). Here, in order to control the energy consumed in the wake-up process, a set of constraints is introduced to limit the number of time an access device (MR or MAP) can change its state from active to idle and vice versa.

In what follows, the *JPEM-CN with CapEx budget* is presented (Section 7.2); then, the *JPEM-WMN with on/off switching constraints* as reported in Boiardi *et al.* (2012a) is illustrated (Section 7.3).

7.2 JPEM-CN with CapEx budget constraints

As already pointed out, the joint planning and energy management model for cellular networks introduced in Section 5.6 is computationally very complex. As a matter of fact, the numerical tests presented in Chapter 5 were obtained by setting the optimality gap at 5% for most of the instances, so as to bound the resolution time to 30 minutes or less. However, the massive increase in complexity when larger instances are considered makes it impossible to examine any real size scenario.

A variation of the JPEM-CN problem has been developed to reduce the complexity of the mathematical model and to improve the consistency of the original formulation, a variation of the JPEM-CN problem has been developed where the CapEx term is removed from objective function (5.7), leaving

$$\varphi \sum_{j\in S}\sum_{k\in K_j}\sum_{t\in T}\epsilon_{jk}\delta_t y_{jkt} + \vartheta \sum_{i\in I_t}\sum_{j\in S}\sum_{t\in T} x_{ijt}\delta_t r_{ij} \tag{7.1}$$

As reported in Section 5.6, parameters ϵ_{jk} represent the power consumed by a BS located in site j with configuration k, parameters δ_t measure the duration of time period t while parameters r_{ij} correspond to the distance between TP i and a BS in j. Decision variables y_{jkt} and x_{ijt} equal 1 if, respectively, a BS in site j with configuration k is active in time t and if Traffic TP i is assigned to a BS located in j during time t. Parameter φ, defined as in Section 5.6, symbolizes the cost of the energy consumption over the network lifetime. Since only the OpEx component is minimized in the new objective function (7.1), β is no longer needed to trade-off between the capital and energy costs; on the other hand, parameter ϑ is used to weigh the importance of the third part of the objective function, which guarantees the quality of the connection between test points and base stations.

The new formulation requires the introduction of an additional parameter B, defining the available capital budget for the installation of the access devices. In order to impose a limit on the maximum CapEx allowed in the network deployment phase, a *budget* constraint is also added to the model:

$$\sum_{j\in S}\sum_{k\in K_j} z_{jk}\gamma_{jk} \leq B \tag{7.2}$$

Parameters γ_{jk} represent the cost of installing a BS with configuration k in site j, while variables z_{jk} are set to 1 if a BS is installed in site j with configuration k. Thus, the JPEM-CN with budget constraints, which will be called *Budget JPEM-CN*, is defined as follows:

$$
\begin{array}{rll}
\min \quad (7.1) & \textbf{OpEx} & \\
& \varphi \sum_{j \in S} \sum_{k \in K_j} \sum_{t \in T} \epsilon_{jk} \delta_t y_{jkt} + \vartheta \sum_{i \in I_t} \sum_{j \in S} \sum_{t \in T} x_{ijt} \delta_t r_{ij} & \\
\text{subject to:} \quad (7.2) & \textbf{CapEx budget constraints} & \\
& \sum_{j \in S} \sum_{k \in K_j} z_{jk} \gamma_{jk} \leq B & \\
(5.8) & \textit{Coverage constraints} & \\
& \sum_{j \in S} \sum_{k \in K_j} a_{ijk} y_{jkt} \geq 1 & \forall i \in I_c \cup I_t, t \in T \\
(5.9) & \textit{Traffic TP coverage constraints} & \\
& x_{ijt} \leq \sum_{k \in K_j} a_{ijk} y_{jkt} & \forall i \in I_t, j \in S, t \in T \\
(5.10) & \textit{BS capacity constraints} & \\
& \sum_{i \in I_t} x_{ijt} p_{it} \leq \sum_{k \in K_j} c_{jk} y_{jkt} & \forall j \in S, t \in T \\
(5.11) & \textit{Traffic TP assignment constraints} & \\
& \sum_{j \in S} x_{ijt} = 1 & \forall i \in I_t, t \in T \\
(5.12) & \textit{Variable } y \textit{ and } z \textit{ linking constraints} & \\
& y_{jkt} \leq z_{jk} & \forall j \in S, k \in K_j, t \in T \\
(5.13) & \textit{Single configuration constraints} & \\
& \sum_{k \in K_j} z_{jk} \leq 1 & \forall j \in S \\
(5.14) - (5.16) & \textit{Domain of decision variables} & \\
& z_{jk}, x_{ijt}, y_{jkt} \in \{0, 1\} & \forall j \in S, k \in K_j, \in I_t, t \in T
\end{array}
$$

Additional parameters used in this formulation and introduced in Section 5.6 include a_{ijk}, equal to 1 if TP i is in the coverage area of a BS placed in site j with configuration k, p_{it}, measuring the traffic provided by Traffic TP i in time period t, and c_{jk}, which represent the capacity of a BS installed in j with configuration k.

7.2.1 Model variations and numerical results

The Budget JPEM-CN has been tested by considering the same scenarios used on the original framework and displayed in Table 5.2:

- "Scenario 1", with 40 candidate sites (CSs), 121 coverage test points (CTPs) and 30 traffic test points (TTPs) on a square area of 2000 $m \times 2000$ m;
- "Scenario 2", with 60 CSs, 676 Coverage TPs and 60 Traffic TPs on a square area of 5000 $m \times 5000$ m;
- "Scenario 3", with 120 CSs, 441 Coverage TPs and 40 Traffic TPs on a square area of 4000 $m \times 4000$ m;
- "Scenario 3a-b-c", a set of test instances having the same characteristics of Scenario 3, but allowing only two BS configurations to be installed in the area (Scenario 3a: $C1$ and $C2$, Scenario 3b: $C1$ and $C3$, Scenario 3c: $C2$ and $C3$).

The value of the CapEx budget B varies according to the dimensions of the studied scenario. Define $\underline{B}$ as the CapEx of the minimum cost topology, that is, the CapEx resulting from the original JPEM-CN applied to the same scenario with $\beta = 0$. Considering $\underline{B}$ as the initial amount for each test instance, values of budget have been tested being 10%, 20% and 30% higher. To obtain the numerical examples reported below, the trade-off parameter ϑ was set to 0.01. Even though the same parameter equals zero in the examples shown in Section 5.7.3, a fair comparison can be carried on between the JPEM-CN framework and its Budget variation; in fact, in case of LTE test instances the objective function component insuring a better connection quality between users and access devices does not have any impact on the problem resolution (see Section 5.6). Finally, once again the optimality gap was set at 5% so as to evaluate the benefits (if any) of the Budget formulation with respect to the original joint framework.

For the sake of completeness, a partial coverage version of the Budget JPEM-CN was also developed. As explained in Section 5.7.2 for the original formulation, here the network service is provided only to those TTPs that are requiring traffic during a certain time period, so that BSs covering only inactive users can be switched off. Parameter m_{it} is introduced to realize the limited coverage of the area, which is equal to 1 if Traffic TP i is active in time interval t. Similarly to the case of the original JPEM-CN, *coverage constraints* (5.8) and *Traffic TP assignment constraints* (5.11) are replaced by constraints (5.17) and (5.18), which guarantee that *every* TP is in the covering radius of at least one *installed* BS but only *active* ones are provided with network service by *tuned-on* access devices. Thus, the partial coverage Budget JPEM-CN can be written as:

$$
\begin{array}{rrll}
\min & (7.1) & \textit{OpEx} & \\
& & \varphi \sum_{j\in S}\sum_{k\in K_j}\sum_{t\in T} \epsilon_{jk}\delta_t y_{jkt} + \vartheta \sum_{i\in I_t}\sum_{j\in S}\sum_{t\in T} x_{ijt}\delta_t r_{ij} & \\
\text{subject to:} & (7.2) & \textit{CapEx budget constraints} & \\
& & \sum_{j\in S}\sum_{k\in K_j} z_{jk}\gamma_{jk} \leq B & \\
& (5.17) & \textbf{Partial coverage constraints} & \\
& & \sum_{j\in S}\sum_{k\in K_j} a_{ijk} z_{jk} \geq 1 & \forall i \in I_c \cup I_t \\
& (5.9) & \textit{Traffic TP coverage constraints} & \\
& & x_{ijt} \leq \sum_{k\in K_j} a_{ijk} y_{jkt} & \forall i \in I_t, j \in S, t \in T \\
& (5.10) & \textit{BS capacity constraints} & \\
& & \sum_{i\in I_t} x_{ijt} p_{it} \leq \sum_{k\in K_j} c_{jk} y_{jkt} & \forall j \in S, t \in T \\
& (5.18) & \textbf{Active TTP assignment constraints} & \\
& & \sum_{j\in S} x_{ijt} = m_{it} & \forall i \in I_t, t \in T \\
& (5.12) & \textit{Variable } y \textit{ and } z \textit{ linking constraints} & \\
& & y_{jkt} \leq z_{jk} & \forall j \in S, k \in K_j, t \in T \\
& (5.13) & \textit{Single configuration constraints} & \\
& & \sum_{k\in K_j} z_{jk} \leq 1 & \forall j \in S \\
(5.14)-(5.16) & & \textit{Domain of decision variables} & \\
& & z_{jk}, x_{ijt}, y_{jkt} \in \{0,1\} & \forall j \in S, k \in K_j, \in I_t, t \in T
\end{array}
$$

Tables 7.1 and 7.2 show the outcomes obtained by applying the Budget JPEM-CN to Scenario 1 and Scenario 2. If the budget parameter B is set to be equal to the minimum topology cost $\underline{B}$, the mathematical model is is not able to provide a solution due to constraints (7.2) being too tight. Therefore, starting from the minimum capital costs of 56000 € and 267000 € for Scenario 1 and 2 respectively (see Tables 5.3 and 5.4, $\beta = 0$), three values of CapEx budget have been calculated as 10%, 20% and 30% higher than $\underline{B}$. Both Tables report

Table 7.1 Summary of the results obtained from the Budget JPEM-CN with total coverage, Scenario 1.

	$B = 61.6\ k$ $\underline{B} + 10\%$	$B = 67.2\ k$ $\underline{B} + 20\%$	$B = 72.8\ k$ $\underline{B} + 30\%$
Time	$1\ h\ 15\ min\ 55\ sec$	$1\ min\ 16\ sec$	$6\ min\ 5\ sec$
CapEx (k€)	58	56 *(-3%)*	68 *(+17%)*
Vs. JPEM-CN, $\beta = 0$	**+4%**	**+0%**	**+21%**
OpEx (k€, 8 y, 0.35€/kWh)	40	18 *(-55%)*	18 *(-55%)*
Vs. JPEM-CN, $\beta = 0$	**-5%**	**-57%**	**-57%**
Installed BSs	20	22	23
Configuration Types	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 5	C2 - 5
	C3 - 18	C3 - 17	C3 - 18
Turned On BSs	t_1 - 16	t_1 - 17	t_1 - 18
	t_2 - 9	t_2 - 10	t_2 - 10
	t_3 - 7	t_3 - 4	t_3 - 4
	t_4 - 9	t_4 - 10	t_4 - 10
	t_5 - 14	t_5 - 15	t_5 - 16
	t_6 - 14	t_6 - 15	t_6 - 15
	t_7 - 15	t_7 - 18	t_7 - 17
	t_8 - 17	t_8 - 18	t_8 - 18

Table 7.2 Summary of the results obtained from the Budget JPEM-CN with total coverage, Scenario 2.

	$B = 293.7\ k$ $\underline{B} + 10\%$	$B = 320.4\ k$ $\underline{B} + 20\%$	$B = 347.1\ k$ $\underline{B} + 30\%$
Time	$2\ min\ 15\ sec$	$1\ min\ 12\ sec$	$1\ min\ 54\ sec$
CapEx (k€)	292	318 *(+9%)*	341 *(+17%)*
Vs. JPEM-CN, $\beta = 0$	**+9%**	**+19%**	**+28%**
OpEx (k€, 8 y, 0.35€/kWh)	115	117 *(+2%)*	114 *(-0.8%)*
Vs. JPEM-CN, $\beta = 0$	**-43%**	**-42%**	**-44%**
Installed BSs	36	35	38
Configuration Types	C1 - 2	C1 - 2	C1 - 3
	C2 - 22	C2 - 25	C2 - 24
	C3 - 12	C3 - 8	C3 - 11
Turned On BSs	t_1 - 30	t_1 - 27	t_1 - 30
	t_2 - 23	t_2 - 22	t_2 - 22
	t_3 - 23	t_3 - 22	t_3 - 22
	t_4 - 23	t_4 - 22	t_4 - 22
	t_5 - 26	t_5 - 24	t_5 - 25
	t_6 - 31	t_6 - 29	t_6 - 30
	t_7 - 31	t_7 - 33	t_7 - 29
	t_8 - 34	t_8 - 30	t_8 - 31

the problem solving time, the capital investments related to the deployed network topology, the operational costs during an eight-year period, the number and type of installed BS as well as the amount of access stations switched on. Percentages in parenthesis refer to the results in column $\underline{B}+10\%$, while percentages in bold report the CapEx and OpEx difference with respect to the results of the original JPEM-CN tested on the same scenario with $\beta = 0$, i.e., minimum cost, unmanaged topology.

The first observation concerns the computational time required by the tested examples. Differently from what expected, the Budget model shows an inconsistent behavior: while for the majority of the instances a solution is reached in a few minutes, in one case the problem is solved in more than one hour (Table 7.1, B=$\underline{B}$+10%). The reason could be the proximity of B to the minimum CapEx value $\underline{B}$. Consider now Tables 7.3 and 7.4, where results for the Budget JPEM-CN with partial area coverage are displayed. Observing in particular the results for Scenario 1 in Table 7.3, it can be noticed that not only the $\underline{B}$+10%, but also the $\underline{B}$+30% instance is highly time consuming. Therefore, *budget constraints* (7.2) and the value of B seem not to be directly responsible for the Budget framework complexity.

Focusing on the percentages of energy savings achievable with growing values of B, Tables 7.1 and 7.2 clearly underline how, over a certain threshold, the model does not provide any further improvements in power consumption reduction. Take for instance Table 7.1, where the results related to Scenario 1 are reported in case of complete network coverage. The big "leap" in energy savings happens for B=$\underline{B}$+20%, when as much as 57% OpEx cutback is reached with respect to the unmanaged minimum cost topology (see Table 5.3) without any extra capital investment. On the other hand, B=$\underline{B}$+10% only brings a total 5% power reduction while B=$\underline{B}$+30% entails a 21% higher CapEx but guarantees no additional decreases in energy expenses. In this case, it is also interesting to compare the devices deployed in the minimum cost topology without network management (1 $C1$, 1 $C2$ and 16 $C3$ BSs) to the access stations installed in correspondence of the decisive power savings increase for B=$\underline{B}$+10% (0 $C1$, 5 $C2$ and 17 $C3$ BSs). As observed for the original JPEM-CN, even maintaining the same value of capital costs, a higher number of small cells replacing bigger ones provides more network flexibility and thus, more opportunities for energy savings. Similar considerations apply to Scenario 2 in Table 7.2, where a great decrease in energy consumption is register for B=$\underline{B}$+10%, while a less pronounced but similar behavior can be identified in Tables 7.3 and 7.4.

Finally, Table 7.5 shows the results from Scenario 3 and its variations by applying the total (first section) and the partial area coverage (second section) Budget JPEM-CN with B =$\underline{B}$+10% is reported. These results can be compared with the ones displayed in Table 5.7, where the same scenarios are solved by means of the complete and partial coverage

Table 7.3 Summary of the results obtained from the Budget JPEM-CN with partial coverage, Scenario 1.

	$B = 61.6\ k$ $\underline{B}$+10%	$B = 67.2\ k$ $\underline{B}$+20%	$B = 72.8\ k$ $\underline{B}$+30%
Time	2 h 17 min	15 min 1 sec	1 h 25 min 53 min
CapEx (k€)	58	67 *(+16%)*	68 *(+17%)*
Vs. JPEM-CN Partial Coverage, $\beta = 0$	**+4%**	**+20%**	**+21%**
OpEx (k€, 8 y, 0.35€/kWh)	32	14 *(-56%)*	14 *(-56%)*
Vs. JPEM-CN Partial Coverage, $\beta = 0$	**-24%**	**-67%**	**-67%**
Installed BSs	20	22	22
Configuration Types	C1 - 1	C1 - 0	C1 - 0
	C2 - 1	C2 - 5	C2 - 5
	C3 - 18	C3 - 17	C3 - 17
Turned On BSs	t_1 - 15	t_1 - 18	t_1 - 18
	t_2 - 10	t_2 - 12	t_2 - 12
	t_3 - 1	t_3 - 1	t_3 - 1
	t_4 - 8	t_4 - 11	t_4 - 11
	t_5 - 14	t_5 - 16	t_5 - 16
	t_6 - 14	t_6 - 15	t_6 - 15
	t_7 - 14	t_7 - 17	t_7 - 16
	t_8 - 16	t_8 - 18	t_8 - 18

Table 7.4 Summary of the results obtained from the Budget JPEM-CN with partial coverage, Scenario 2.

	$B = 293.7\ k$ $\underline{B} + 10\%$	$B = 320.4\ k$ $\underline{B} + 20\%$	$B = 347.1\ k$ $\underline{B} + 30\%$
Time	1 min 48 sec	8 min 48 sec	6 min 31 sec
CapEx (k€)	293	320 *(+9%)*	342 *(+17%)*
Vs. JPEM-CN Partial Coverage, $\beta = 0$	**+10%**	**+20%**	**+28%**
OpEx (k€, 8 y, 0.35€/kWh)	87	80 *(-8%)*	74 *(-15%)*
Vs. JPEM-CN Partial Coverage, $\beta = 0$	**-57%**	**-61%**	**-64%**
Installed BSs	35	35	39
Configuration Types	C1 - 3	C1 - 3	C1 - 3
	C2 - 19	C2 - 22	C2 - 24
	C3 - 13	C3 - 10	C3 - 12
Turned On BSs	t_1 - 29	t_1 - 28	t_1 - 29
	t_2 - 17	t_2 - 18	t_2 - 19
	t_3 - 7	t_3 - 7	t_3 - 7
	t_4 - 15	t_4 - 15	t_4 - 14
	t_5 - 21	t_5 - 19	t_5 - 21
	t_6 - 23	t_6 - 25	t_6 - 29
	t_7 - 27	t_7 - 26	t_7 - 25
	t_8 - 31	t_8 - 30	t_8 - 29

Table 7.5 Important results obtained from the Budget JPEM-CN with total and partial coverage (B = $\underline{B}$+10%), Scenario 3 and its variations.

	Scenario 3	Scenario 3a	Scenario 3b	Scenario 3c
Total Coverage:				
Budget (k€)	150.7	231	210.1	150.7
CapEx (k€)	150	-	202 *(+35%)*	141 *(-6%)*
OpEx (k€, 8 y, 0.35€/kWh)	47	-	198 *(+321%)*	46 *(-2%)*
Installed BSs	C1 - 0	C1 - -	C1 - 6	C1 - n.a.
	C2 - 13	C2 - -	C2 - n.a.	C2 - 12
	C3 - 34	C3 - n.a.	C3 - 22	C3 - 21
Turned On BSs in t_3	C1 - 0	C1 - -	C1 - 6	C1 - n.a.
	C2 - 13	C2 - -	C2 - n.a.	C2 - 12
	C3 - 5	C3 - n.a.	C3 - 5	C3 - 7
Turned On BSs in t_8	C1 - 0	C1 - -	C1 - 6	C1 - n.a.
	C2 - 12	C2 - -	C2 - n.a.	C2 - 12
	C3 - 15	C3 - n.a.	C3 - 13	C3 - 16
Partial Coverage:				
Budget (k€)	150.7	231	210.1	150.7
CapEx (k€)	150	-	210 *(+40%)*	150 *(-0%)*
OpEx (k€, 8 y, 0.35€/kWh)	11	-	53 *(+381%)*	11 *(-0%)*
Installed BSs	C1 - 0	C1 - -	C1 - 6	C1 - n.a.
	C2 - 12	C2 - -	C2 - n.a.	C2 - 12
	C3 - 30	C3 - n.a.	C3 - 30	C3 - 30
Turned On BSs in t_3	C1 - 0	C1 - -	C1 - 0	C1 - n.a.
	C2 - 0	C2 - -	C2 - n.a.	C2 - 0
	C3 - 7	C3 - n.a.	C3 - 7	C3 - 7
Turned On BSs in t_8	C1 - 0	C1 - -	C1 - 2	C1 - n.a.
	C2 - 2	C2 - -	C2 - n.a.	C2 - 2
	C3 - 21	C3 - n.a.	C3 - 22	C3 - 21

versions of the original JPEM-CN. In all cases, the original and Budget frameworks reach very close outcomes; however, predictably, when only large cells are allowed to be installed in the considered area (Scenario 3a), the Budget variation fails in providing a feasible solution that satisfies at the same time the traffic coverage and the budget constraints.

From the presented results it is possible to conclude that, when a budget constraint is imposed by the network operator on the capital investments, the framework proposed in Section 7.2.1 represents an effective and reliable formulation for the deployment and management of cellular networks.

7.3 JPEM-WMN with on/off switching constraints

The JPEM-WMN framework as originally formulated (see Section 6.5.2) allows the access devices, namely mesh routers (MRs) and mesh access points (MAPs), to be turned on and put to sleep as many times as necessary to reach the best trade-off between CapEx and OpEx. Although the costs of a device activation from the idle state have not been considered in the problem formulation, continuous changes in the state of MRs and MAPs can influence negatively the energy bill as well as compromise the correct device functioning.

To cope with this issue, an interesting variation of the JPEM-WMN model was developed and presented in Boiardi *et al.* (2012a), where a maximum limitation is introduced on the number of times each installed BS can change its state from on to off and vice versa. Two sets of auxiliary variables were added to the original formulation:

$$v_{jt} = \begin{cases} 1 & \text{if a MR installed in site } j \in S \text{ change its state} \\ & \text{from time } t-1 \text{ to time } t \in T, \\ 0 & \text{otherwise.} \end{cases} \tag{7.3}$$

$$g_{jt} = \begin{cases} 1 & \text{if a MAP installed in site } j \in S \text{ change its state} \\ & \text{from time } t-1 \text{ to time } t \in T, \\ 0 & \text{otherwise.} \end{cases} \tag{7.4}$$

The new *auxiliary constraints* (7.5) to (7.8), replacing respectively the non linear expressions $v_{jt} \geq |y_{jt} - y_{jt-1}|$ and $g_{jt} \geq |r_{jt} - r_{jt-1}|$, help counting the number of state changes for each access device:

$$v_{jt} \geq y_{jt} - y_{jt-1} \qquad \forall j \in S, t \in T/\{t_1\} \tag{7.5}$$

$$v_{jt} \geq y_{jt-1} - y_{jt} \qquad \forall j \in S, t \in T/\{t_1\} \tag{7.6}$$

$$g_{jt} \geq r_{jt} - r_{jt-1} \qquad \forall j \in S, t \in T/\{t_1\} \tag{7.7}$$

$$g_{jt} \geq r_{jt-1} - r_{jt} \qquad \forall j \in S, t \in T/\{t_1\} \tag{7.8}$$

State change constraints (7.9) and (7.10) limit the number of state switches to a chosen value η_1 for routers and η_2 for access points.

$$\sum_{t \in T/\{t_1\}} v_{jt} \leq \eta_1 \qquad \forall j \in S \tag{7.9}$$

$$\sum_{t \in T/\{t_1\}} g_{jt} \leq \eta_2 \qquad \forall j \in S \tag{7.10}$$

Finally, domain constraints have to be added for the auxiliary variables:

$$v_{jt} \in \{0, 1\} \qquad \forall j \in S, t \in T/\{t_1\} \tag{7.11}$$

$$g_{jt} \in \{0, 1\} \qquad \forall j \in S, t \in T/\{t_1\} \tag{7.12}$$

The JPEM-WMN with on/off switching constraints, from now on denominated *On/Off JPEM-WMN*, is defined as:

$$
\begin{array}{rll}
\min \quad (6.27) & \textit{CapEx and OpEx} & \\
& \beta \sum_{j \in S} (z_j \gamma_j + p_j w_j) + (1-\beta) \sum_{j \in S} \sum_{t \in T} (\epsilon_j y_{jt} + \psi_j r_{jt}) \Delta(t) & \\
\text{subject to:} \quad (6.28), (6.29) & \textit{MC assignment constraints} & \\
& \sum_{j \in S} x_{ijt} = 1 & \forall i \in I, t \in T \\
& x_{ijt} \leq a_{ij}(y_{jt} + r_{jt}) & \forall i \in I, j \in S, t \in T \\
(6.30) & \textit{BS installation constraints} & \\
& z_j + w_j \leq 1 & \forall j \in S \\
(6.31), (6.32) & \textit{MR/MAP activation constraints} & \\
& y_{jt} \leq z_j \, , \; r_{jt} \leq w_j & \forall j \in S, t \in T \\
(6.33) & \textit{Flow conservation constraints} & \\
& \sum_{l \in S} (f_{ljt} - f_{jlt}) + \sum_{i \in I} d_{it} x_{ijt} = f_{jNt} & \forall j \in S, t \in T \\
(6.34), (6.35) & \textit{BS/Link capacity constraints} & \\
& \sum_{i \in I} x_{ijt} d_{it} \leq c_j (y_{jt} + r_{jt}) & \forall j \in S, t \in T \\
& f_{ljt} + f_{jlt} \leq u_{jl} k_{jl} & \forall j, l \in S, t \in T \\
(6.36) - (6.38) & \textit{Link usage constraints} & \\
& f_{ljt} + f_{jlt} \leq u_{jl}(y_{jt} + r_{jt}) \, , \; f_{ljt} + f_{jlt} \leq u_{jl}(y_{lt} + r_{lt}) & \forall j, l \in S, t \in T \\
& f_{jNt} \leq m r_{jt} & \forall j \in S, t \in T \\
(6.39) - (6.41) & \textit{Link existence constraints} & \\
& k_{jl} \leq z_j + w_j \, , \; k_{jl} \leq z_l + w_l \, , \; k_{jl} \leq b_{jl} & \forall j, l \in S \\
(6.42) & \textit{Best MC/BS assignment constraints} & \\
& y_{J_l^{(i)} t} + r_{J_l^{(i)} t} + \sum_{h=l+1}^{l_i} x_{i J_l^{(i)} t} \leq 1 & \forall i \in I, t \in T \\
& & \forall l : 1 ... B_i - 1 \\
(7.5) - (7.8) & \textbf{Auxiliary constraints} & \\
& v_{jt} \geq y_{jt} - y_{jt-1} \, , \; v_{jt} \geq y_{jt-1} - y_{jt} & \forall j \in S, t \in T / \{t_1\} \\
& g_{jt} \geq r_{jt} - r_{jt-1} \, , \; g_{jt} \geq r_{jt-1} - r_{jt} & \forall j \in S, t \in T / \{t_1\} \\
(7.9), (7.10) & \textbf{On/off switching constraints} & \\
& \sum_{t \in T / \{t_1\}} v_{jt} \, , \; \sum_{t \in T / \{t_1\}} g_{jt} \leq \eta_1 & \forall j \in S \\
(6.43) - (6.46), (7.11), (7.12) & \textit{Domain of decision and auxiliary variables} & \\
& x_{ijt}, y_{jt}, r_{jt}, z_j, w_j, k_{jl} \in \{0, 1\} & \forall i \in I, j, l \in S, t \in T \\
& v_{jt}, g_{jt} \in \{0, 1\} & \forall j \in S, t \in T / \{t_1\}
\end{array}
$$

The model parameters are defined as in Section 6.5. Parameters γ_j and p_j represent respectively the installation costs of a MR or MAP installed in site j, while their power consumption is measured by ϵ_j and ψ_j. $\Delta(t)$ is the duration of time period t. Parameters c_j, m and u_{jl} quantify the access capacity of a BS located in site j, the MAP's Internet access capacity and the capacity of the link between BSs installed in sites j and l. Parameters a_{ij} and b_{jl} are equal to 1 if, respectively, MC i is in the coverage area of BS j and if a link between BSs installed in sites j and l is possible. The traffic provided by MC i in time period t is represented by d_{it}, while B_i counts the number of BSs covering MC i. As for the model variables, z_j and w_j are equal to 1 if a MR or MAP is installed in site j, while y_{jt} and r_{jt} are equal to 1 if an installed MR or MAP is active in time period t. Variables x_{ijt} express if MC i is assigned to a BS installed in site j in time t and variables k_{jl} equal 1 if a link between BSs installed in j and l exists. Finally, variables f_{jlt} and f_{jNt} represent the flow between BSs located in j and l and the flow between a MAP installed in j and the Internet (N) during time t.

7.3.1 Model variations and numerical results

Numerical results were produced to compare the modified formulation described above with the original JPEM-WMN framework. The same test scenarios reported in Table 6.2 have been considered:

- "Small", counting 13 candidate sites (CSs) and 60 mesh clients (MCs) on a square area of 1000 $m \times$ 1000 m;
- "Medium", counting 40 CSs and 130 MCs on a square area of 1500 $m \times$ 1500 m;
- "Large", counting 64 CSs and 240 MCs on a square area of 2500 $m \times$ 2500 m.

In this case, only the *standard* traffic profile is taken into account, that is, each MC is randomly assigned by the instance generator with a traffic value ranging between 1 and 10 Mb/s. Also, the limit on the number of state changes has been set to 1 for both MRs and MAPs (η_1 and η_2, respectively).

As done for the original formulation described in Section 6.5.2, different problem variations were tested:

- **The two-step approach**, which divides the On/Off JPEM-WMN in two separate phases. First, the minimum cost network topology is obtained by running the model proposed above by setting β to 1, that is, by dropping the OpEx term from the objective function; then, the management of the deployed devices is optimized by means of the framework proposed in Capone *et al.* (2012b).

- **The on/off switching constraints relaxation**, representing the original JPEM-WMN problem, where no limit is imposed on the number of state changes of the access devices;
- **The cellular comparison**, where only mesh access points (MAPs) can be installed in the area. Here, the multi-hop behavior typical of WMNs is replaced by a topology where every access device is directly connected to the backbone and thus, to the Internet.
- **The partial covering-relaxed problem**, where the network service is provided only to active customers in every time instance. Installed access points that cover only idle customers can be turned off. In this case, as reported in Section 6.5.3 for the original framework, an additional binary parameters h_{it} have to be introduced, which is equal to 1 is MC i is providing traffic in time period t. Once again, *MC assignment constraints* (6.29) have to be replaced by constraints (6.47), responsible for limiting the network coverage only to active MCs.

Table 7.6 compares the energy saving percentages obtained from the On/Off JPEM-WMN and the ones resulting from the original version of the framework. Each percentage entry, identifying the savings achieved in correspondence of a certain value of the trade-off parameter β, refers to the energy requirements of the same test scenario when $\beta = 1$. In that case, the operational expenses are ignored and the model simply provides a network design optimization according to the minimum installation costs criterion. The percentages reported in parenthesis show the additional savings that can be reached if the state switching constraints are relaxed, i.e., if the access stations are free to change their activity state. Important energy savings can be obtained when installation and management are jointly optimized. As expected, the relaxation of the on/off switching constraints allows even lower power expenditures; the deployed network is more flexible, and only the access devices that are necessary to route the traffic or cover the MCs are maintained on.

A better insight on the effect of the on/off constraints relaxation on the network topology is provided in Table 7.7, where the results obtained by exploiting the *two-step* approach are also

Table 7.6 Energy saving percentages obtained from the JPEM-WMN with or without the on/off switching constraints in all test scenarios (percentages are referred to the cases of $\beta = 1$).

		Small	Medium	Large
On/off JPEM-WMN	$\beta = 0.8$	15.37%	7.75%	12.12%
	$\beta = 0.5$	20.50%	10.33%	12.40%
	$\beta = 0.1$	23.77%	14.67%	15.46%
JPEM-WMN	$\beta = 0.8$	20.49% (*+6.05%*)	12.39% (*+5.04%*)	27.66% (*+6.62%*)
	$\beta = 0.5$	27.66% (*+9.17%*)	14.98% (*+5.18%*)	20.87% (*+9.59%*)
	$\beta = 0.1$	27.66% (*+5.10%*)	20.80% (*+7.26%*)	23.11% (*+9.05%*)

Table 7.7 Summary of the results obtained from the JPEM-WMN with or without the on/off switching constraints, "Small" scenario.

On/off JPEM-WMN	$\beta = 1$	two-step	$\beta = 0.5$	$\beta = 0.1$
CapEx (€)	2600	2600	2800	3200
Energy (Wh/day)	4392	3717 (*-15.36%*)	3492 (*-20.49%*)	3348 (*-23.77%*)
Installed MRs	11	11	12	12
Installed MAPs	1	1	1	2
JPEM-WMN	$\beta = 1$	two-step	$\beta = 0.5$	$\beta = 0.1$
CapEx (€)	2600	2600	2800	2800
	-	**-**	**-**	**-12.50%**
Energy (Wh/day)	4392	3492 (*-20.49%*)	3177 (*-27.66%*)	3177 (*-27.66%*)
	-	**-6.05%**	**-9.17%**	**-5.10%**
Installed MRs	11	11	12	12
Installed MAPs	1	1	1	1

reported. For the two problem formulations, the Table illustrates the CapEx, the daily energy consumption of the installed network and the number of deployed routers and gateways. The percentages in parenthesis represent the energy consumption reduction with respect to the case of $\beta = 1$, that is, when no energy management is taken into account. Finally, percentages in bold show the variations of CapEx and energy consumption achieved when the original model formulation is considered instead of On/Off. As displayed in the Table, when the switching state constraints are not included in the formulation, the topology remains unchanged for $\beta = 1$ and $\beta = 0.5$; however, if the value of β is decreased at 0.1, the original JPEM-WMN model allows as much as 12.5% CapEx savings. Lower power expenses and, potentially, lower capital costs are justified by a high adaptability of the installed topology, whose access devices are freely managed to serve the users located in the area.

In Table 7.8, the largest test scenario is considered and three sets of results are gathered. The top part of the table shows the results obtained by applying the On/Off JPEM-WMN, the middle part displays the results of the cellular variation of the On/Off JPEM-WMN while the bottom one reports the outcomes of the cellular variation applied to the original JPEM-WMN formulation (as in Table 6.5). Once again, the capital costs and the daily energy expenses are displayed, together with the number of access devices installed in the area. While the percentages in parenthesis refer to the same test instance where $\beta = 1$, here the bold font identifies the percentage difference with respect to the results reported in the above part: bold percentages in the "On/Off JPEM-WMN, cellular comparison" sector point out to the "On/Off JPEM-WMN" results, while the ones in the "JPEM-WMN, cellular comparison" sector refer to the "On/Off JPEM-WMN, cellular comparison" sector. The results shown in the Table reveal the benefits provided by the high flexibility of wireless mesh networks. When

Table 7.8 Summary of the results obtained from the cellular variation of the JPEM-WMN with or without the on/off switching constraints, “Large” scenario.

On/off JPEM-WMN	$\beta = 1$	$\beta = 0.5$	$\beta = 0.1$
CapEx (€)	9600	9600	12600
Energy (Wh/day)	16416	14634 (*-10.85%*)	14121 (*-13.98%*)
Installed MRs	42	44	51
Installed MAPs	3	2	6
On/off JPEM-WMN, cellular comparison	$\beta = 1$	$\beta = 0.5$	$\beta = 0.1$
CapEx (€)	18000	18400	22800
Vs. On/Off JPEM-WMN	**+87.50%**	**+91.66%**	**+80.95%**
Energy (Wh/day)	19440	17442 (*-10.28%*)	16146 (*-16.94%*)
Vs. On/Off JPEM-WMN	**+18.42%**	**+19.19%**	**+14.34%**
Installed MAPs	45	46	57
JPEM-WMN, cellular comparison	$\beta = 1$	$\beta = 0.5$	$\beta = 0.1$
CapEx (€)	18000	18800	21600
Vs. On/Off JPEM-WMN, cellular comparison	**-**	**+2.17%**	**-5.26%**
Energy (Wh/day)	19440	15876 (*-18.33%*)	15120 (*-22.22%*)
Vs. On/Off JPEM-WMN, cellular comparison	**-**	**-8.98%**	**-6.35%**
Installed MAPs	45	47	54

only MAPs are allowed in the network design process, both installation and operation costs face a sensible increase. The reason is to be found in the fact that only the most expensive devices can be deployed (the price of gateways is double the cost of simple routers) and, therefore, the typical adaptability of WMNs cannot be fully exploited. The same behavior can be observed for the cellular variation of both the On/Off and the original JPEM-WMN; however, in the latter case, CapEx and power expenses tend to be slightly lower due to the relaxation of the state change constraints, which allows the installed devices to be activated and put to sleep without restrictions.

Finally, Table 7.9 displays the percentages of energy savings that can be achieved by offering network service to active mesh clients only, compared to the savings obtained by the complete coverage On/Off JPEM-WMN. Predictably, the relaxed formulation enables

Table 7.9 Energy saving percentages obtained from the On/Off JPEM-WMN and from its partial covering-relaxed variations in all test scenarios (percentages are referred to the cases of $\beta = 1$).

		Small	Medium	Large
	$\beta = 0.8$	15.37%	7.75%	12.12%
On/off JPEM-WMN	$\beta = 0.5$	20.50%	10.33%	12.40%
	$\beta = 0.1$	23.77%	14.67%	15.46%
Partial coverage	$\beta = 0.8$	10.65% (*+7.26%*)	14.46% (*+7.28%*)	13.20% (*+1.23%*)
On/Off	$\beta = 0.5$	10.65% (*+1.43%*)	14.46% (*+4.61%*)	13.47% (*+1.23%*)
JPEM-WMN	$\beta = 0.1$	16.36% (*+3.60%*)	20.97% (*+6.24%*)	20.04% (*+5.42%*)

slightly higher power savings with respect to the reference framework due to the lower number of customers requiring coverage; however, more striking saving values are prevented by the effect of constraints (7.9) and (7.10), which limit to one the number of state changes allowed to each access device. As foreseeable, removing the on/off switching constraints results in a more efficient network management, as shown in Table 6.7 and displayed in Figure 6.3.

CHAPTER 8

HEURISTIC RESOLUTION

8.1 Introduction

As already pointed out, the joint planning and energy management problem for cellular networks (JPEM-CN) is computationally very expensive. This complexity has limited the analysis only to the small test instances presented in Section 5.7, where a maximum of 120 candidate sites and 60 traffic test points are considered in a single scenario. Moreover, the solutions are never optimal but always obtained by stopping the optimization at 5% gap to the lower bound (or below, in some cases).

In order to simplify the application of the joint framework and allow the investigation of larger test examples, an heuristic method has been developed. By separating the design and the operation management problems and addressing only specific time periods, the proposed heuristic computes a partial topology that serves as initial solution for the original JPEM-CN. This way, the solving time for the toy scenarios displayed in Table 5.2 is reduced while the resolution of real-size instances is at last possible.

In this chapter, the technique is explained and illustrated (Section 8.2). It is evaluated in Section 8.3, where the results from the toy scenarios are compared to the results obtained from the JPEM-CN. Finally, Section 8.4 introduces new, bigger test instances and shows the performance of the heuristic in terms of solving time.

8.2 Heuristic Method for JPEM-CN

The joint planning and energy management problem for cellular networks as described in Section 5 is a powerful planning tool, able to find the best network deployment based on its installation costs and its energy saving capabilities. The framework has proven its effectiveness and benefits compared to a more traditional approach where the operation management is performed on a pre-installed network; however, the computational complexity of the model formulation limits its application only to small-size test instances.

The heuristic developed during the doctoral research aims at decreasing the solving time for toy examples and allowing the resolution of test scenarios whose size is comparable with real-life situations. The idea lying behind the proposed method is that a solution can be reached faster if the JPEM-CN framework is provided in input with a partial topology from which the optimization can start off. The heuristic approach develops according to the

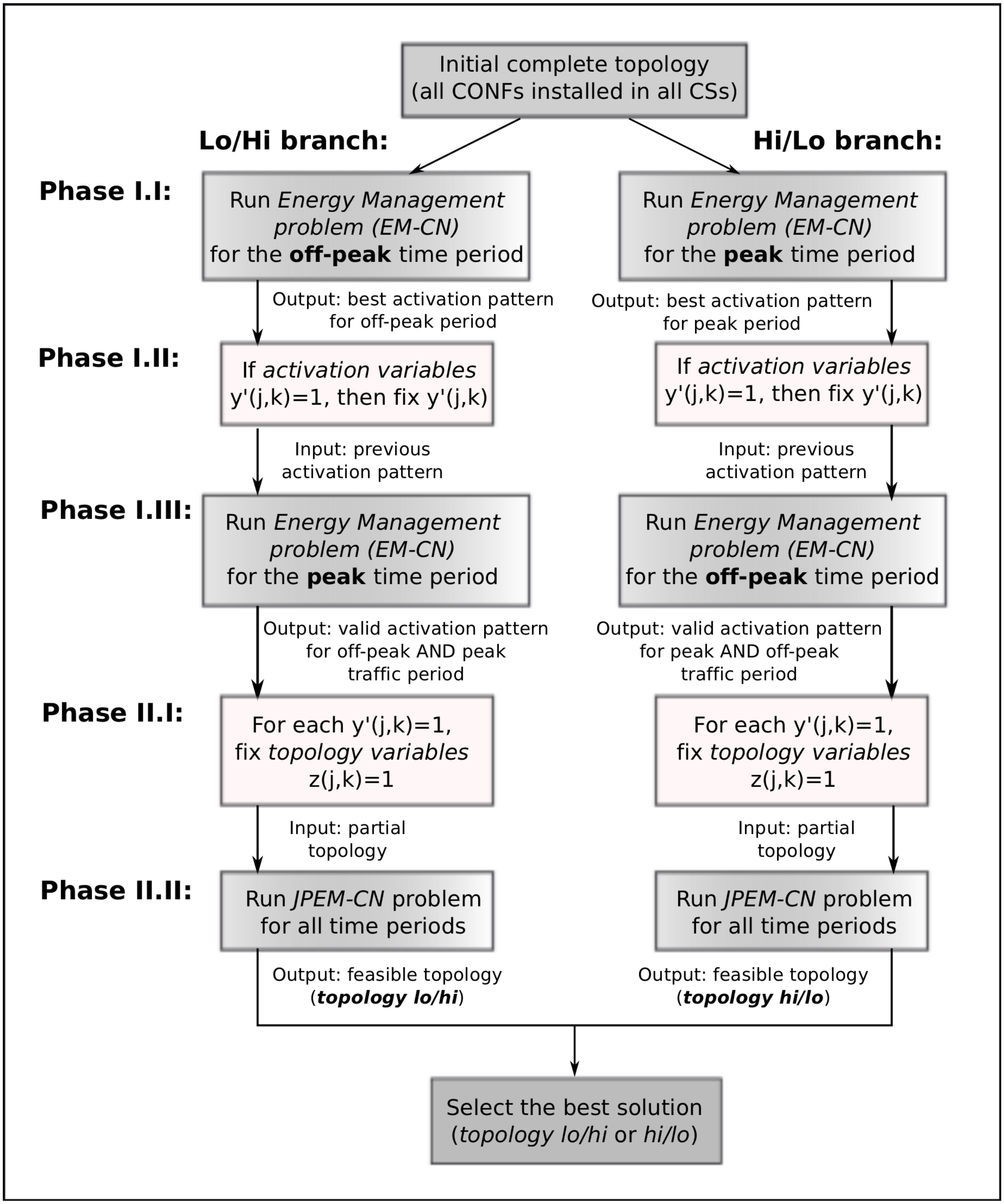


Figure 8.1 Schematics of the heuristic method for JPEM-CN.

diagram reported in Figure 8.1. In what follows, its phases are separately presented and described in more detail.

Preliminary - Selection of the considered time periods

The division of the day in multiple time periods, each one characterized by a different traffic profile value, and the necessity of topological continuity between them constitute one of the most challenging aspects of the JPEM-CN. Naturally, in order to reduce the problem complexity and formulate a heuristic, one of the first decisions to be taken is how to deal with the time dimension. In particular, it is fundamental to determine which time periods should be examined and in which way they should be connected to one another.

Between the eight time intervals considered for the cellular network examples and displayed in Figure 5.1, two of them can be identified as particularly significant:

- The *peak traffic time* t_8, during which the highest traffic volume has to be served by an elevated number of access stations;
- The *off-peak time* t_3, when the highest number of access devices can potentially be turned off to reduce the energy expenses.

Thus, in the heuristic's *phase I*, only the intervals t_8 and t_3 and the corresponding traffic values are taken into account, while the remaining periods of the day are temporary neglected and reconsidered in *phase II*. As it happens in the original problem formulation, a connection is maintained between these time periods; more details on the issue are provided in the next phases.

Phase I.I - Energy Management problem for time t_r

Once the time periods of interest have been chosen, their traffic information are exploited *in succession* to perform the operation management of a fictitious complete topology, where all the base station configurations are installed in every candidate site. Such an initial topology has been chosen to guarantee that the selected activation pattern is effectively the most energy efficient one for the first time. In this regard, it is important to note that the order in which the time instances are considered influences the outcome of the heuristic; therefore, the heuristic has been tested by analyzing first the peak time t_8 and then the off-peak time t_3 and vice versa. Here, to avoid any confusion, the first and second time periods to be evaluated are identified respectively as t_r and t_s.

Consider now t_r and the corresponding registered traffic data. Given a complete topology, the energy management problem for cellular networks (EM-CN) is used to find the *BS activation pattern with lowest energy consumption* during t_r. The EM-CN can be modeled by borrowing parameters, variables and constraints from the original and Budget versions of the JPEM-CN; however, modifications are necessary to drop the time indexes and to account for the pre-installed access devices.

$$\min \quad \varphi \sum_{j\in S}\sum_{k\in K_j} \epsilon_{jk}\delta_{t_r} y'_{jk} \tag{8.1}$$

$$\text{subject to:} \quad \sum_{j\in S}\sum_{k\in K_j} a_{ijk} y'_{jk} \geq 1 \qquad \forall i \in I_c \cup I_t \tag{8.2}$$

$$x'_{ij} \leq \sum_{k\in K_j} a_{ijk} y'_{jk} \qquad \forall i \in I_t, j \in S \tag{8.3}$$

$$\sum_{i\in I_t} x'_{ij} p_{it_r} \leq \sum_{k\in K_j} c_{jk} y'_{jk} \qquad \forall j \in S \tag{8.4}$$

$$\sum_{j\in S} x'_{ij} = 1 \qquad \forall i \in I_t \tag{8.5}$$

$$\sum_{k\in K_j} y'_{jk} \leq 1 \qquad \forall j \in S \tag{8.6}$$

$$x'_{ij}, y'_{jk} \in \{0,1\} \qquad \forall j \in S, k \in K_j, i \in I_t \tag{8.7}$$

As in the previous formulations, parameters ϵ_{jk} and c_{jk} represent the energy consumption and the capacity of a BS located in j with configuration k, δ_{t_r} is the duration in hours of time t_r and p_{it_r} measures the traffic offered by Traffic TP i during time t_r. Parameter φ symbolizes the cost of the power consumption over the network lifetime. Since the network topology is known, installation variables are excluded from the formulations; on the other hand, the time index has been dropped for the activation variables y'_{jk}, which are equal to 1 if the access station located in j with configuration k is part of the activation pattern, and variables x'_{ij}, equal to 1 if the traffic of TP i is served by a BS located in j. As the connection quality is intrinsically guaranteed for LTE scenarios (see Section 5.6), objective function (8.1) only minimizes the energy expenses of the complete topology operated in t_x. *Coverage constraints* (8.2) ensure a complete area coverage by imposing that all the TPs are within the service area of at least one active BS, while (8.3) assign each Traffic TPs to an active access station. *Capacity constraints* (8.4) limit the traffic assigned to each BS to its maximum capacity, and *assignment constraints* (8.5) impose that each Traffic TP is only assigned to one BS. *Activation constraints* (8.6) replace *configuration constraints* (5.13) in the original formulation to assure that only one BS configuration can be active in the same CS, and *binary constraints* (8.7) set the domain for the decision variables. Finally, note that the described EM-CN problem is solved to optimality.

Phase I.II - Consistency of the activation pattern

At this point, through the EM-CN model, the best access station activation pattern has been found for a complete topology in time period t_r. In order to keep track of the chosen BSs in the next step of the heuristic, and so guarantee a *connection between the considered time intervals*, the corresponding activation variables y'_{jk} are *fixed* to their current value: *if* $y'_{jk} = 1$ *then fix* y'_{jk}. In other words, the access stations active in t_r are forced to be switched on also during t_s.

Phase I.III - Energy Management problem for time instance t_s

Consider now time instance t_s (t_8 or t_3, according to which one has been previously examined). The operation management performed in *phase I.I* is repeated on the same complete topology to accommodate the traffic provided by the TTPs in t_s. However, this time the EM-CN model is not free to select *all* the access stations to be switched on. Instead, since the turned-on BSs during t_r have been fixed in *phase I.II*, the network management framework will *integrate* the previous active pattern with additional devices to provide the extra capacity required in the second analyzed time period.

Thus, the result of the *double energy management* process (*phase I.I* to *phase I.III*) represents the best solution for time t_r (remember that the supplementary BSs switched on in *phase I.III* can be turned off when not needed) but only a feasible solution for time t_s. This observation is fundamental to understand which time period and associated activation pattern have the strongest influence on the final network energy consumption.

Phase II-I - Partial Topology as JPEM-CN input

As a matter of fact, the activation pattern resulting from *phases I.I* to *I.III* can be considered as the *set of installed access devices* necessary to satisfy the traffic requirements during time periods t_r and t_s. No information is known on the performance of the chosen pattern during the remaining intervals; however, it is known that the selected BSs represent a good solution for two significant time instances and the *most energy-efficient topology* at least during t_r.

Therefore, it is worth to assume that the chosen activation pattern constitutes a good initial topology to provide in input to the joint framework as described in Section 5.6. To do so, the JPEM-CN installation variables z_{jk} are set to 1 to match the active BSs in the pattern: *if* $y'_{jk} = 1$ *then fix* $z_{jk} = 1$.

Phase II-II - JPEM-CN resolution

When the remaining time instances are taken into account, the activation pattern during t_r and t_s may likely result unfeasible due to changes in space of the offered traffic. Therefore, the last step of the developed heuristic considers the set of access devices only as a *partial* initial topology. As showed in *phase II.I*, the BSs that are part of the pattern are imposed to the JPEM-CN model as pre-installed access stations; then, according to the CapEx and OpEx trade-off typical of the joint formulation, additional devices are deployed and the whole topology is managed to follow the network traffic variations. In all tested scenarios, the trade-off parameter β were set to 1; furthermore, since the quality of the connection is automatically guaranteed for LTE instances, parameter ϑ were set to 0. Note that, differently from the original JPEM-CN (for which the optimality gap was set to 5%), the joint framework is here solved to optimality.

This procedure can be repeated considering in turn $\{t_r = t_3, t_s = t_8\}$ and $\{t_r = t_8, t_s = t_3\}$. Depending on the order in which the time periods are examined, the heuristic produces as output two different topologies. When t_r is equal to the peak traffic time t_8, the resulting solution is denominated *hi/lo topology* (*high* traffic instance first, then *low* traffic one); on the other hand, when t_r is equal to the off-peak period t_3, the the output is referred to as *lo/hi topology* (the *low* traffic instance is analyzed before the *high* traffic one). The solutions deriving from the *hi/lo* and *lo/hi branches* of the heuristic show different characteristics and solving time. In the next Sections, the performance of both branches is evaluated in relation to the numerical results obtained from the JPEM-CN framework; then, additional tests are presented and discussed to assess the heuristic capabilities.

8.3 Resolution approach and numerical examples

As in the case of the joint formulation, the heuristic method presented in Section 8.2 was implemented in AMPL and solved using CPLEX. In particular, unlike the original joint problem, which were solved accepting an optimality gap of 5%, both the EM-CN and the JPEM-CN problems included in the heuristic were solved to the optimum (unless indicated otherwise).

In order to prove its validity, the proposed approach was tested on the cellular network scenarios created for the JPEM-CN framework and reported in Table 5.2:

- "Scenario 1", counting 40 candidate sites (CSs), 121 coverage test points (CTPs) and 30 traffic test points (TTPs) on a square area of 2000 m × 2000 m;

Table 8.1 Results obtained by applying JPEM-CN and the heuristic resolution to Scenario 1.

	$\beta = 0$	$\beta = 0$ (two-step)	$\beta = 1$ (joint)	Heuristics (hi/lo)	Heuristics (lo/hi)
Time	44 *sec*	1 *sec* (oper)	25 *min* 11 *sec*	14 *sec*	12 *sec*
Objective Function	56000	95443	81076	82777 *(+2%)*	91623 *(+13%)*
Lower Bound	-	-	77024	+7.5%	+19%
CapEx (k€)	56	56	62 *(+11%)*	64 *(+14%)*	72 *(+29%)*
OpEx (k€, 8 y, 0.35€/kWh)	42.52	39.44 *(-5%)*	19.07 *(-55%)*	18.77 *(-56%)*	19.62 *(-54%)*
Installed BSs	18	18	17	19	18
Configuration Types	C1 - 1	C1 - 1	C1 - 0	C1 - 0	C1 - 0
	C2 - 1	C2 - 1	C2 - 5	C2 - 5	C2 - 6
	C3 - 16	C3 - 16	C3 - 12	C3 - 14	C3 - 12
Turned On BSs	t_1 - 18	t_1 - 16	t_1 - 17	t_1 - 17	t_1 - 17
	t_2 - 18	t_2 - 9	t_2 - 10	t_2 - 10	t_2 - 10
	t_3 - 18	t_3 - 4	t_3 - 4	t_3 - 7	t_3 - 4
	t_4 - 18	t_4 - 8	t_4 - 10	t_4 - 11	t_4 - 10
	t_5 - 18	t_5 - 13	t_5 - 15	t_5 - 15	t_5 - 15
	t_6 - 18	t_6 - 14	t_6 - 15	t_6 - 14	t_6 - 14
	t_7 - 18	t_7 - 16	t_7 - 15	t_7 - 16	t_7 - 16
	t_8 - 18	t_8 - 17	t_8 - 17	t_8 - 18	t_8 - 16

- "Scenario 2", counting 60 CSs, 676 Coverage TPs and 60 Traffic TPs on a square area of 5000 $m \times 5000$ m;
- "Scenario 3", counting 120 CSs, 441 Coverage TPs and 40 Traffic TPs on a square area of 4000 $m \times 4000$ m;
- "Scenario 3a-b-c", a set of test instances having the same characteristics of Scenario 3, but allowing only two BS configurations to be installed in the area (Scenario 3a: $C1$ and $C2$, Scenario 3b: $C1$ and $C3$, Scenario 3c: $C2$ and $C3$).

To observe the impact of the first time period on the construction of the network topology, both the *hi/lo* and *lo/hi branches* of the heuristic were performed on each instance. Tables 8.1 and 8.2 show the results obtained solving, respectively, Scenario 1 and Scenario 2 with the JPEM-CN model (see Section 5.6) and the heuristic method. Joint framework examples are given by setting the trade-off parameter β to 0, that is to say disregarding the energy expenses and minimizing only the installation costs in the objective function, or to 1, in order to enable the joint minimization of CapEx and OpEx. The *two-step* variation of JPEM-CN is also displayed, which simulates the traditional approach where first, the network design, and then, the operation management are optimized. For each test instance, the tables report the following entries:

1. CPLEX resolution time;
2. Value of the objective function, consisting in the sum of CapEx and OpEx (except for the case of $\beta = 0$, when only deployment costs are taken into account);

Table 8.2 Results obtained by applying JPEM-CN and the heuristic resolution to Scenario 2.

	$\beta = 0$	$\beta = 0$ (two-step)	$\beta = 1$ (joint)	Heuristics (hi/lo)	Heuristics (lo/hi)
Time	25 *sec*	1 *sec* (oper)	1 *min* 51 *sec*	7 *sec*	9 *sec*
Objective Function	267000	464801	411013	432570 *(+5%)*	461838 *(+12%)*
Lower Bound	-	-	391952	+10%	+18%
CapEx (k€)	267	267	277 *(+4%)*	300 *(+12%)*	336 *(+26%)*
OpEx (k€, 8 y, 0.35€/kWh)	202.64	197.80 *(-3%)*	134.01 *(-34%)*	132.57 *(-35%)*	125.84 *(-38%)*
Installed BSs	23	23	30	35	33
Configuration Types	C1 - 5	C1 - 5	C1 - 2	C1 - 2	C1 - 3
	C2 - 11	C2 - 11	C2 - 21	C2 - 23	C2 - 22
	C3 - 7	C3 - 7	C3 - 7	C3 - 10	C3 - 6
Turned On BSs	t_1 - 23	t_1 - 18	t_1 - 26	t_1 - 26	t_1 - 28
	t_2 - 23	t_2 - 14	t_2 - 22	t_2 - 21	t_2 - 21
	t_3 - 23	t_3 - 15	t_3 - 23	t_3 - 21	t_3 - 21
	t_4 - 23	t_4 - 14	t_4 - 22	t_4 - 21	t_4 - 21
	t_5 - 23	t_5 - 15	t_5 - 23	t_5 - 23	t_5 - 22
	t_6 - 23	t_6 - 18	t_6 - 27	t_6 - 28	t_6 - 27
	t_7 - 23	t_7 - 21	t_7 - 28	t_7 - 29	t_7 - 26
	t_8 - 23	t_8 - 22	t_8 - 30	t_8 - 31	t_8 - 30

3. Percentage difference between the objective function resulting from *phase II.II* of the heuristic and the lower bound of the same test instance solved with JPEM-CN by setting $\beta = 1$. Due to the altered nature of the problem when $\beta = 0$, in which case no importance is given to the reduction of the operation energy consumption during the network design phase, the corresponding lower bounds and respective percentage differences are not considered;
4. CapEx, expressed in thousands of Euro and corresponding to the value of the first term of the objective function;
5. OpEx of the network, constituting the second term of the objective function and calculated over a 8 year period by considering the energy cost for business users of 0.35 €$/kWh$;
6. Number and type of access stations installed in the area;
7. Number of access stations switched on during every time period.

Moreover, percentages in parenthesis refer to the objective function value, installation and operational expenses obtained for the unmanaged minimum cost topology (JPEM-CN,$\beta = 0$).

First of all, observe the values of the objective function obtained for Scenario 1 and Scenario 2 using the *hi/lo* and *lo/hi* heuristic resolutions. Comparing these results to the corresponding values acquired from the JPEM-CN by imposing $\beta = 1$, it is evident how the proposed method provides very good approximations of the solutions computed by the joint framework. The heuristic objective function value exceeds the joint formulation one only by 2% and 5% in the *hi/lo* case for Scenario 1 and 2, while the percentages grow to

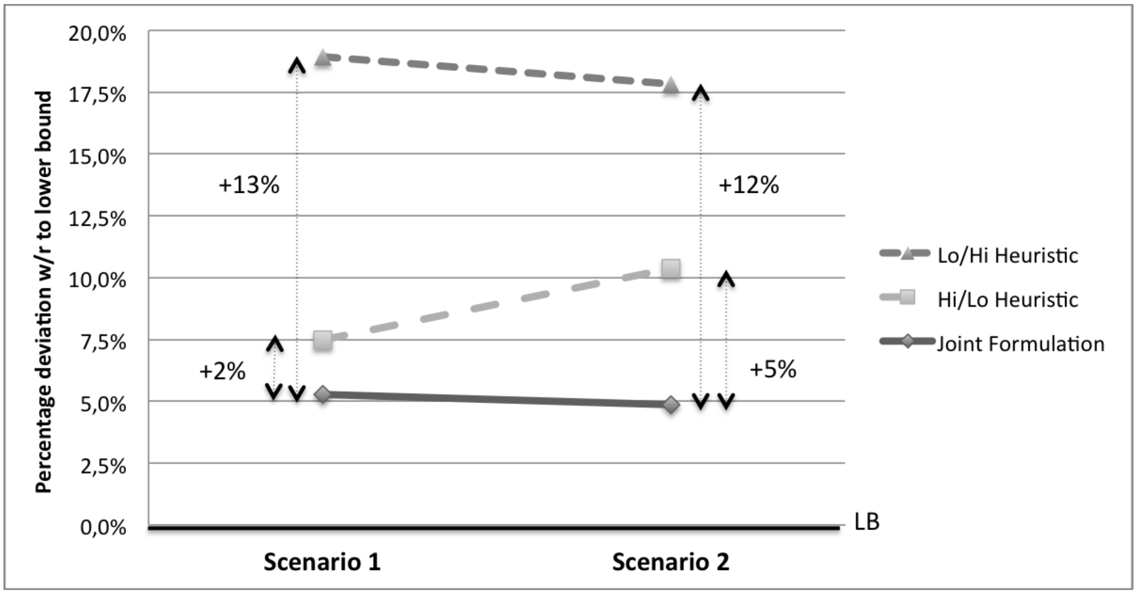


Figure 8.2 Heuristic method performance: percentage deviation from the lower bound and from the joint framework solutions.

13% and 12% when the *lo/hi* resolution is considered. However, taking into account that the JPEM-CN instances are solved by setting a 5% gap to optimality, it is fundamental for the correct evaluation of the heuristic performance to examine the *hi/lo* and *lo/hi* results in correlation to the lower bounds of the $\beta = 1$ JPEM-CN solution. Figure 8.2 displays the percentage deviation of the solutions obtained from the joint and heuristic formulations from the lower bounds for Scenario 1 and 2. The percentage difference between the heuristic solutions (dashed lines) and the joint formulation ones (dark gray line) are also reported in the chart. Showing percentage differences of +7.5% and +10% for Scenario 1 and 2 respectively, the objective function of the *hi/lo branch* seems to maintain a closer proximity to the lower bound of the joint formulation than the *lo/hi branch*, for which the percentages grow at +19% and +18%. Extending the analysis to the values of CapEx and OpEx, the heuristic seem to perform similarly to the original model: in both cases, the initial installation investments undergo modest increases with respect to the minimum cost topology (+12% and +14% for the *hi/lo*, +29% and +26% for the *lo/hi*) to ensure high energy savings in the network operation management phase. In most of the examples, the computed OpEx is even lower than the one calculated by the JPEM-CN with $\beta = 1$, indicating that the presented technique is successfully driven toward the installation of an effective energy-aware network topology. In this sense, the heuristic seems to reproduce the behavior of the JPEM-CN framework when the trade-off parameter is greater than one, that is, when the operational costs are given higher weight then the CapEx in the model's objective function (see Tables 5.3 and 5.4 for a comparison). Now, if the number and types of deployed access devices are considered, the same tendency to install small and medium size BSs typical of the JPEM-CN is found again in the heuristic resolution. The choice of the time periods to be examined, as well as the importance given to the sole energy-aware operation in the first phases of the heuristic procedure, guarantee a high level of flexibility to the resulting network topology. Lastly, note that the computational time is of the order of seconds in all cases.

Further results from Scenarios 3 and its variations 3a, 3b and 3c are gathered in Table 8.3. For each instance, the $\beta = 1$ JPEM-CN solution is directly compared to the outcomes of the *hi/lo* and *lo/hi* heuristic. Once again, the solving time is reported first, then the value of the objective function. The lower bound of the solution is displayed for the joint framework instances, while the difference percentage to the lower bound is calculated for the heuristic results. Capital and operational expenditures are measured in thousands of Euro; finally, the number and configuration of the installed devices are presented.

As observed for the previous examples, the heuristic performs very well in terms of cost values and deployed topology. The objective functions never diverge more than +6% from the lower bounds of the respective joint problem results; likewise, the heuristic's CapEx and OpEx are almost identical or even slightly lower than the ones computed by the original formulation. No significant differences can be identified between the JPEM-CN and the heuristic resolutions in the amount or type of installed access stations. On the other hand, the computational time required by CPLEX to solve some of the instances appears much higher than in the examples reported in Tables 8.1 and 8.2 for Scenario 1 and Scenario 2. While the *hi/lo branch* of the heuristic is able to solve Scenario 3a much faster than the joint framework (less than 2 minutes, compared to 20 minutes 25 seconds in the JPEM-CN case), Scenario 3 and 3c seem to be more challenging, requiring respectively almost 17 minutes and 8 minutes 12 seconds to be solved. Interestingly, the *lo/hi branch* behaves differently, showing much lower resolution times for most of the examples.

The outstanding results obtained by testing the heuristic on small scenarios paved the way to the analysis of bigger instances to measure the performance of the proposed heuristic procedure when real-size problems are taken into account. In the next Section, new scenarios are introduced and the heuristic outcomes are presented and described.

Table 8.3 Important results obtained applying JPEM-CN ($\beta = 1$) and the heuristic resolution to Scenario 3 and its variations.

	Scenario 3	Scenario 3a	Scenario 3b	Scenario 3c
Total Coverage:				
Time	2 *min* 22 *sec*	20 *min* 25 *sec*	17 *sec*	43 *sec*
Objective Function	182379	311288	386516	182966
Lower Bound	176960	295056	384391	177301
CapEx (k€)	136	240	190	137
OpEx (k€, 8 y, 0.35€/kWh)	45.38	71.29	196.52	45.97
Installed BSs	C1 - 0	C1 - 0	C1 - 6	C1 - n.a.
	C2 - 12	C2 - 24	C2 - n.a.	C2 - 12
	C3 - 16	C3 - n.a.	C3 - 10	C3 - 17
Heuristics (hi/lo):				
Time	16 *min* 56 *sec*	1*min* 49 *sec*	3 *min* 25 *sec*	8 *min* 12 *sec*
Objective Function	182569 *(+0.1%)*	311432 *(+0.04%)*	385399 *(-0.2%)*	183393*(+0.2%)*
Vs. Lower Bound	+3%	+6%	+0.2%	+3%
CapEx (k€)	137	240 *(+0%)*	189 *(-0.5%)*	138 *(+0.7%)*
OpEx (k€, 8 y, 0.35€/kWh)	45.57	71.43 *(+0.2%)*	196.40 *(+0.1%)*	45.39 *(-1%)*
Installed BSs	C1 - 0	C1 - 0	C1 - 6	C1 - n.a.
	C2 - 12	C2 - 24	C2 - n.a.	C2 - 12
	C3 - 17	C3 - n.a.	C3 - 9	C3 - 18
Heuristics (lo/hi):				
Time	37 *sec*	50 *sec*	2 *min* 42 *sec*	26 *sec*
Objective Function	182393 *(+0%)*	311577 *(+0.1%)*	386443 *(+0.01%)*	181261 *(-1%)*
Vs. Lower Bound	+3%	+6%	+0.5%	+2%
CapEx (k€)	137	240 *(+0%)*	190 *(+0%)*	136 *(-0.7%)*
OpEx (k€, 8 y, 0.35€/kWh)	45.39	71.58 *(+0.4%)*	196.44 *(+0.1%)*	45.26 *(-1%)*
Installed BSs	C1 - 0	C1 - 0	C1 - 6	C1 - n.a.
	C2 - 12	C2 - 24	C2 - n.a.	C2 - 12
	C3 - 17	C3 - n.a.	C3 - 10	C3 - 16

Table 8.4 Parameters used to generate the heuristic test scenarios.

	Area (km^2)	CSs	CTPs	TTPs	Allowed Configurations
Scenario A	6×6	130	961	50	All
Scenario B	6×6	200	961	70	All
Scenario C	7×7	220	1296	80	All
Scenario D	8×8	250	1681	60	All
Scenario E	8×8	400	1681	90	All
Scenario F	8×8	500	1681	150	All
Scenario G	10×10	450	2601	90	All
Scenario H	10×10	500	2601	110	All
Scenario I	10×10	600	2601	150	All
Scenario L	10×10	700	2601	180	All
Scenario M	15×15	1000	5576	200	All

8.4 Performance evaluation on real-size test scenarios

The numerical examples presented in Section 8.3 highlighted the heuristic's capability to reproduce the behavior of the joint design and energy management problem formulation. Keeping the computational time low, the approach provides as output a flexible network topology whose CapEx are only moderately higher than the minimum cost topology ones, and whose OpEx are similar or lower than the ones computed with the JPEM-CN framework. At this point, larger test instances need to be generated to observe the performance of the heuristic and further confirm its validity. To do so, the same instance generator (IG) described in Section 5.7.1 was used. Eleven test scenarios were created; their names and features are reported in Table 8.4. As displayed in the table, these scenarios present different values of coverage area as well as different number of Traffic TPs and CSs. The objective is to measure the heuristic resolution time in each case, especially when many customers or possible sites for access devices are considered. If the heuristic will prove to be able to solve real-size scenarios in a reasonable amount of time, it will be used as a basis to extend the research on the joint network planning and design concept, up to now impeded by the JPEM-CN model complexity.

Table 8.5 illustrates the results produced by solving Scenario A to Scenario M. In particular, for both versions of the heuristic, the table displays the CPLEX resolution time, the objective function and the values of capital and operational expenditures necessary to the calculated topology. Also, percentages in parenthesis measure the difference between the *lo/hi* and the *hi/lo* solving time and resulting objective function. At a glance, it can be noticed that the *hi/lo* and *lo/hi branches* perform very similarly in terms of computed CapEx and OpEx. Nevertheless, the *hi/lo* version overcomes the *lo/hi* one in almost all

Table 8.5 Important results obtained applying the heuristic resolution to new test scenarios.

	Time (hh:mm:ss)	O.F.	CapEx (k€)	OpEx (k€)
Scenario A (hi/lo)	1:04	563053	337	226.05
Scenario A (lo/hi)	3:28	565009	339	226.01
Scenario B (hi/lo)	9:56	467577	300	167.58
Scenario B (lo/hi)	30 ***(-95%)***	486650 ***(+4%)***	316	170.65
Scenario C (hi/lo)	2:04	594235	394	200.24
Scenario C (lo/hi)	6:18	612995	412	200.99
Scenario D (hi/lo)	57	829572	540	289.57
Scenario D (lo/hi)	25 *(-9%)*	835618 *(+1%)*	544	291.62
Scenario E (hi/lo)	14:19	616883	460	156.88
Scenario E (lo/hi)	2:51 ***(-81%)***	632573 ***(+3%)***	474	158.57
Scenario F (hi/lo)	11:54	655264	475	180.26
Scenario F (lo/hi)	4:02 ***(-66%)***	672758 ***(+3%)***	490	182.76
Scenario G (hi/lo)	2:35	1128532	760	368.53
Scenario G (lo/hi)	1:20 *(-48%)*	1152847 *(+2%)*	783	369.85
Scenario H (hi/lo)	4:44	1065544	747	318.54
Scenario H (lo/hi)	1:38 ***(-65%)***	1079456 ***(+1%)***	760	319.46
Scenario I (hi/lo)	2:13:12	992152	746	246.15
Scenario I (lo/hi)	44:25 ***(-67%)***	997441 ***(+1%)***	751	246.44
Scenario L (hi/lo)	1:59:27	914199	683	231.20
Scenario L (lo/hi)	31:21 ***(-74%)***	927951 ***(+2%)***	695	232.95
Scenario M (hi/lo)	18:06	2461629	1656	805.63
Scenario M (lo/hi)	15:56 *(-12%)*	2467287 *(+2%)*	1662	805.29

cases, reaching at the same time slightly lower energy expenses *and* installation costs. However, another factor should be taken into account. Observe the column where the resolution times are reported. With the exemption of Scenario A and C, where the *hi/lo* heuristic produces better and faster results, the *lo/hi* version has the advantage of drastically reducing the required computational time at the cost of modest increases in the objective function value. The reported percentage differences show that the calculation of a solution can be accelerated by as much as 95% if the off-peak time is examined before the peak one during the heuristic resolution. Particularly significant are the cases of Scenario I and L. Here, if the *hi/lo* procedure is applied, the instance resolution requires respectively 2 hours 13 minutes and 2 hours. Adopting the *lo/hi* approach instead, the computational time is reduced by as 67% and 74% at the cost of only 1% and 2% increase in the value of the objective function.

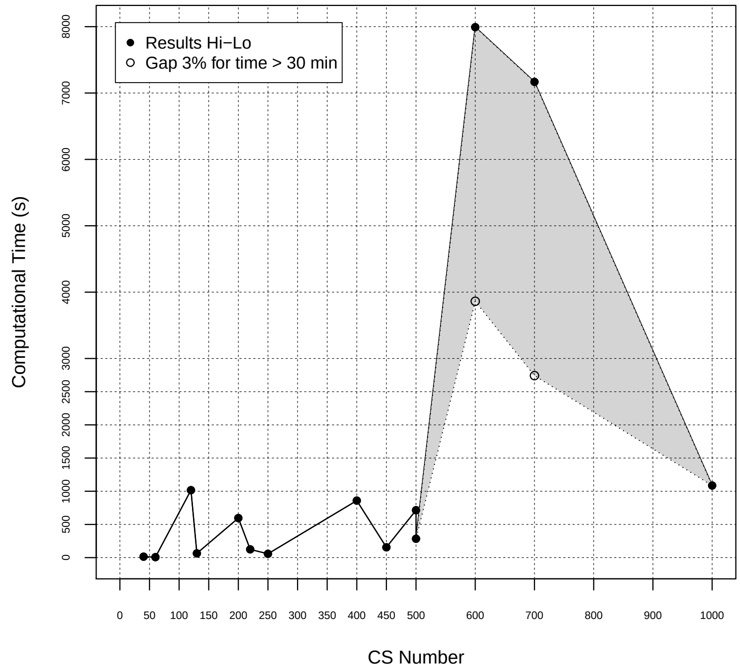
In light of these considerations, it appears clear that both versions of the developed heuristic present their strength and weakness. If, on one hand, the *hi/lo* approach can guarantee lower capital investments and energy consumption in the network operation phase, on the other hand the *lo/hi* procedure ensures much lower resolution times provided that a modest increase in the objective function is accepted. The “best” solution may depend on the situation; however, in general, the choice of one between the *hi/lo* and *lo/hi* approaches should be made by bearing in mind that the main goal of an heuristic method is to obtain a good solution in a short time.

In order to understand which heuristic procedure should be used based on the characteristics of the scenario of interest, it may be useful to identify the solving time trend in relation to different parameters. Figure 8.3, Figure 8.4 and Figure 8.5 plot the resolution times obtained from the *hi/lo* (circle symbol, subfigures (a)) and the *lo/hi* (triangle symbol, subfigures (b)) approaches when Scenarios A to M are ordered by:

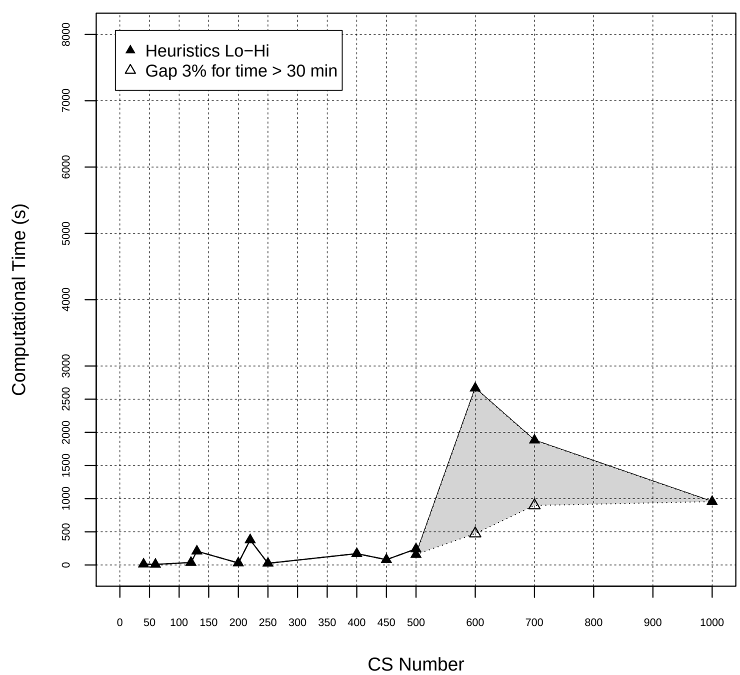
- Number of candidate sites in the considered area (Figure 8.3);
- Number of traffic test points in the considered area (Figure 8.4);
- Number of candidate sites per traffic test point (Figure 8.5).

Observe the figures, neglecting for a moment the colored area. The time required by the heuristic to solve the tested instances seems to be independent by any particular characteristics. Rather, Scenario I and L, which present similar features in terms of number or CSs and Traffic TPs, appear to be the outliers, especially if the much lower solution time of the biggest Scenario M is taken into account. Consider now the light grey area delimited on the lower side by empty circles or triangles, according to which of the two heuristic resolutions is examined. To reduce the high computational time of specific scenarios, a gap greater than zero can be set for the heuristic optimization models. Thus, the empty symbols located in correspondence of the most time consuming instances report the solving time of the same scenario when the EM-CN and JPEM-CN incorporated in the heuristic are no longer solved to optimality, but by setting an optimality gap of 3%. The grey-colored areas underline the change in the solving time curves when the new time values are considered. Selecting a gap of 3%, the resolution time of Scenario I is decreased from 2 hours 13 minutes to 1 hour 4 minutes (*hi/lo* procedure) and from 44 minutes to less than 8 minutes (*lo/hi* procedure); the time reduction comes at the modest price of, respectively, +1% and +2% increase in the objective function value. Similarly, when the optimality gap is set to 3%, Scenario L can be solved in 45 minutes (vs. almost 2 hours, *hi/lo* procedure) and 15 minutes (vs. 31 minutes, *lo/hi* procedure) with only +2% increase in the objective function in both cases.

On the whole, the developed heuristic approach proved to be effective and rather fast with most of the tested instances. The availability of two different procedures, the *hi/lo* and the *lo/hi*, allows the user to choose between a more precise outcome or a much lower computational time. Moreover, to further reduce the solving times, it has been demonstrated that an optimality gap of 3% can be set to speed up the resolution without significantly affecting the value of the objective function.

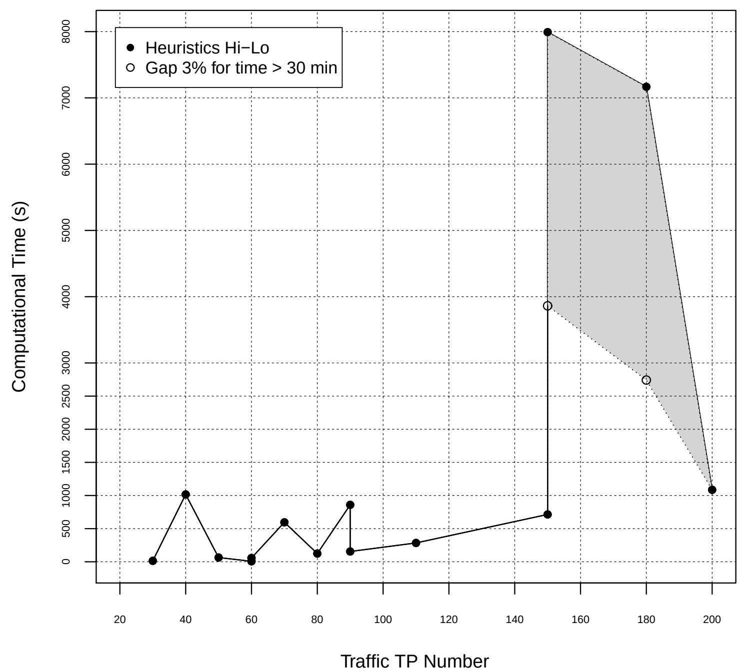


(a) *Hi/Lo resolution.*

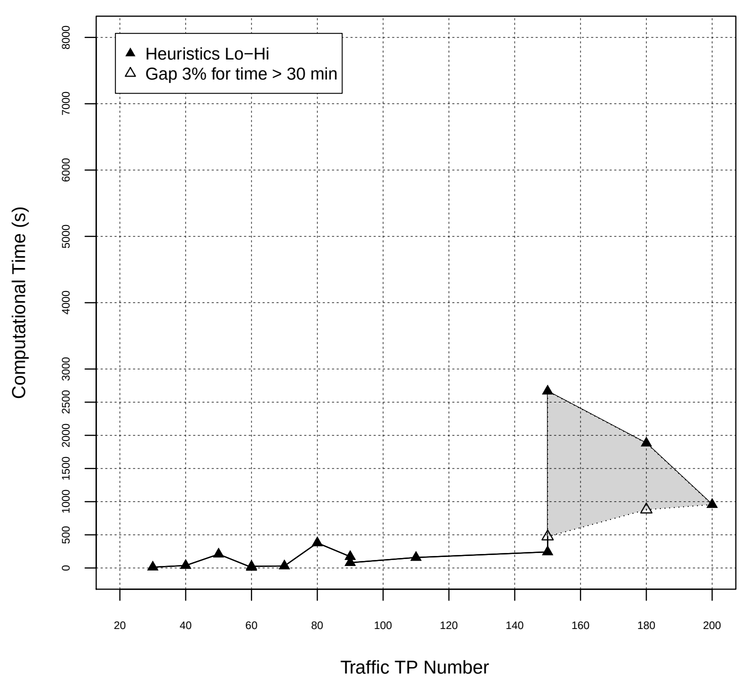


(b) *Lo/Hi resolution.*

Figure 8.3 Computational time, instances ordered by number of CS.

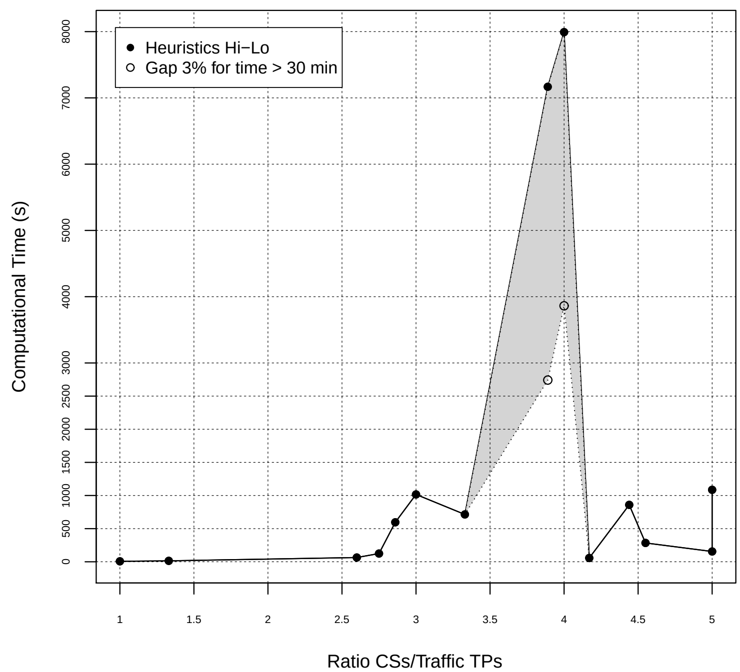


(a) *Hi/Lo resolution.*

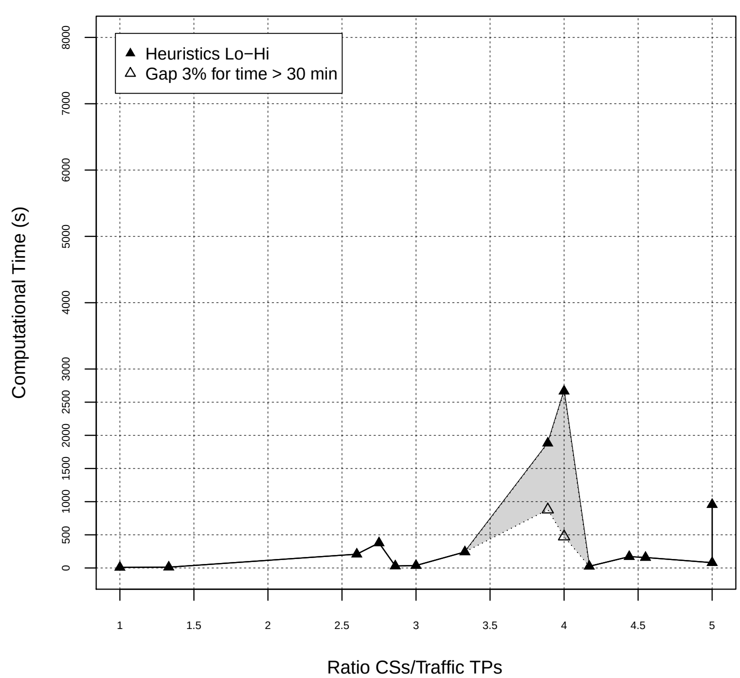


(b) *Lo/Hi resolution.*

Figure 8.4 Computational time, instances ordered by number of Traffic TPs.



(a) *Hi/Lo resolution.*



(b) *Lo/Hi resolution.*

Figure 8.5 Computational time, instances ordered by number of CS per Traffic TP.

CHAPTER 9

GENERAL DISCUSSION

Legacy wireless access networks (WANs) are typically designed regardless of energy efficiency issues; the planning objective is to minimize the installation costs while guaranteeing complete area coverage and connection quality in any load condition, especially during peak traffic periods. In recent years, the rising demand for pervasive mobile communication access increased not only the amount of customers to be served, but also the awareness of the environmental impact. Therefore, if on one hand the capacity of the current networks has to be upgraded to be able to manage the extra traffic, on the other hand new energy-aware techniques should to be taken into account and introduced in the regular network functioning. In this regard, different approaches have been proposed, mainly aiming at powering off unnecessary access stations during low load periods to reduce the power waste. However, when *cell sleeping* procedures are applied to legacy access networks, only minor energy savings can be obtained: although overprovisioned, such networks are mainly composed by large, high power access devices that can hardly be turned off due mostly to their wide area coverage.

The research presented in this doctoral thesis originates from these considerations, claiming that *an energy-aware network design is the key to obtain an effective energy-aware network management*. In other words, the network can be provided with enough flexibility to follow the traffic variations only if an energy-aware operation management is considered during the planning stages. To prove this assertion, the joint planning and energy management problem (JPEM) was developed and presented in its general characteristics in Chapter 4. Assuming no pre-existent topology, for the first time in literature the proposed framework jointly minimizes the capital expenditures (CapEx) related to the network installation and the operational and management expenditures (OpEx) over the network lifetime in order to choose the most energy-efficient network deployment in respect of capital investment limitations. Different topologies can be produced by tuning a *trade-off parameter*, used to regulate the relative importance of the capital and operational expenses in the objective function. When the OpEx term is disregarded, the minimum cost topology is obtained; conversely, if the joint optimization is enabled, the model is forced to reduce not only the capital but also the operational costs. At the price of modest increases in the CapEx expenses, the resulting topologies are more flexible, strategically deploying a high number of small and medium size cells that allow the operation management mechanism to reach significant energy savings.

The proposed formulation has been adapted to two types of wireless access technology. The joint planning and energy management problem for cellular networks (JPEM-CN) is presented in Chapter 5. Three types of access stations have been made available to be installed. Numerical results obtained by six test scenarios confirmed that network topologies designed by taking into account the future power-aware operation reach energy savings of about 60% with respect to the unmanaged minimum cost topology. To carry out a fair comparison, a *two-step* model variation was developed to simulate a more traditional approach where first, the minimum cost topology is deployed and then, the operation of the installed topology is managed. As expected, results showed that only limited savings on the order of 5% can be reached by managing a pre-installed minimum cost topology due to the inflexibility typical of networks designed ignoring any energy efficiency consideration. A *partial covering* variation of the JPEM-CN was proposed to study the model performance when only active customers in the area have to be provided with network service; this way, access devices covering just idle users can be put to sleep. Although not applicable in current network architectures, such a coverage technique would be used in case of a future separation of the signaling and data network, in which case large, constantly active signaling cells would be responsible for the total area coverage, while small cells would provide network service only to active customers. Predictably, the registered energy savings increased, reaching 70% with respect to the minimum cost unmanaged topology and 37% with respect to the total coverage case. Finally, the last variation examined for the cellular version of the JPEM involves the introduction of a maximum budget on the capital expenses. The CapEx term in the object function is dropped while a new set of constraints caps the installation costs to the predetermined limit. The *Budget JPEM-CN*, described in Chapter 7, was developed to model possible hard constraints imposed by the network operator on the network capital investments; results proved that the variation obtains comparable results to the original formulation in a similar amount of time.

In addition to cellular networks, the joint framework has been adjusted to fit the characteristics of wireless access networks (JPEM-WMN, presented in detail in Chapter 6). The same joint optimization principles described for cellular networks apply in this case; however, only two access devices are allowed to be deployed in the area, having same coverage and capacity capabilities: mesh routers, providing network access for the mesh clients and connecting to other routers and gateways through point to point links, and mesh access points, similar to routers but connected directly to the wired backbone. Test results on mesh scenarios highlighted energy savings around 25% to 30% when the joint framework is used, compared to the unmanaged minimum cost topology; the lower energy savings observed for WMNs are due to the limited variety of available access devices and prove once more the importance of the topology flexibility for an effective power-aware management. Again, a *two-step* approach was introduced to fairly evaluate the model performance, showing power reduction of less than 10% in all examples. Moreover, a set of other variations was tested on the JPEM-WMN. Besides the *partial covering* problem, which is able to provide energy savings 9% to 15% higher than the total coverage model, a *MAPs only* variant was developed to disable the multi-hop characteristics of mesh networks and replicate the behavior or a cellular one. An alternative form of JPEM-WMN considers variable capacity for the backbone wireless links according to the access station mutual distance. Also, in the *On/Off JPEM-WMN* formulation presented in Chapter 7, new constraints are added to limit the number of state changes (from on to off and vice versa) for each access station, the objective being to preserve the device functionality and reduce the energy waste during the activation transition.

Finally, an ad hoc heuristic method was developed to obtain faster results and allow the solution of real size instances. In particular, the heuristic approach was tested on the cellular network problem, which turned out to be more computationally expensive than the mesh network counterpart. The idea underlying the proposed technique is that the complexity of the original JPEM-CN could be highly reduced if an initial topology was provided in input to the model; therefore, the heuristic computes a partial topology by selecting an energy-aware BS activation pattern during two specific time periods in the day. Given in input to the joint framework, the partial topology is integrated and made feasible for the whole day. When tested on the same toy scenario used for the JPEM-CN, the heuristic showed results only 2% to 5% higher than the joint framework ones in the best cases, while solving time are greatly decreased in almost all cases. Eleven additional test instances were generated to assess the heuristic performance with realistic size examples. The heuristic approach successfully solved every scenario, whereof the larger one counted 1000 Candidate Sites and 200 Traffic Test Points. The resolution time overtakes 30 minutes only in two cases, but keeps below 20 minutes for the remaining nine instances. Overall, the developed heuristic proved to be an effective tool, rather precise and fast in reaching a solution even when large instances were considered.

CHAPTER 10

CONCLUSION

The growing demand for telecommunications services is drawing attention on the current state of the supporting infrastructure, which needs to be widened and upgraded, as well as on the ICT sector energy footprint, that can no longer be ignored. On the other hand, from the mobile operators' point of view, this uninterrupted spread translates in higher expenses for the installation and management of new devices. In this context, *green networking* has become one of the most actual topics concerning the telecommunications sector. With the aim of decreasing the energy consumption of current networks, researchers have recently tackled the energy-aware network design and operation issue for both wired and wireless networks. However, the *relationship between network planning and operation energy efficiency* is an aspect of the problem so far disregarded.

Focusing on wireless systems, the research project tried to fill this gap by demonstrating the influence of the network topology on the effectiveness of a power-aware network management. In particular, the network *flexibility*, defined as the capacity of the topology to adapt to the traffic demand variation in time and space, is claimed to be the key requirement to enable high energy savings in the management phase. In order to prove these assertions, the joint planning and energy management problem (JPEM) was developed. The mathematical framework jointly minimizes the network installation expenses and its expected operational costs. By regulating the relative importance of the CapEx and OpEx terms through a trade-off parameter, multiple network topologies are obtained. When the power expenditures are ignored, the minimum installation cost network is deployed; on the other hand, when a modest increase in the capital investments are tolerated, the JPEM computes the *best network topology based on its energy savings potentials in the operation stage*. Therefore, the proposed optimization tool offers the opportunity to design the network configuration that best complies with the different cost requirements and, at the same time, shows the possible advantages attainable from a cell sleeping mechanism applied to the selected topology.

10.1 Achievements of the doctoral research

During the doctoral research period, the following objectives were accomplished.

10.1.1 Joint Planning and Energy Management of Cellular Networks

The JPEM framework was adapted to the cellular access technology (JPEM-CN). In order to test the joint formulation, a daily traffic variation pattern was defined; also, believing that the availability of different size cells is fundamental to follow the traffic fluctuations and maximize the energy savings, three access station categories (macro, micro and pico cells) were allowed in cellular instances. Results computed on LTE instances showed that, when the OpEx are ignored during the planning stage, the installed topologies are in general composed by the minimum number of cells; the network structure presents a substantial group of pico and micro access stations, while macro cells are deployed in smaller number. The coexistence of a mixture of different cells could lead to believe in the effectiveness of an energy-aware management of the network. However, the opposite effect was verified: when a power-efficient operation is applied to the minimum cost topology, negligible savings around 5% can be reached compared to the non managed network operation. The situation changes when CapEx and OpEx are jointly minimized. By increasing the influence of the energy expenditures, more access stations are deployed. Micro cells, providing the lower power consumption per unit of covered area, are the ones experiencing the highest increase as the OpEx acquire more importance in the model objective function. The number of pico cells slightly grows, while macro cells are reduced or excluded from the topology. As a result, the network energy consumption is decreased of about 35% to 60%, depending on the considered scenario and on the trade-off value, at the cost of an increment of CapEx lower than 15%.

10.1.2 Joint Planning and Energy Management of Wireless Mesh Networks

The JPEM was reformulated to adjust to wireless mesh access technology (JPEM-WMN). As in the cellular case, traffic variations during the day were considered; however, only two types of same size access devices (router or gateway) can compose a mesh topology. Numerical results were obtained through a set of Wi-Fi mesh test instances. Here, the effect of the proposed joint framework is remarkable but weakened by the reduced choice in terms of access station types; nonetheless, power savings between 20% and 30% are achieved for most test scenarios, compared to savings below 10% reached when the minimum cost topology is managed. Once again, when OpEx are given more weight, the number of installed devices increase without noticeable difference between the routers' and gateways' growth rate.

10.1.3 Joint Planning and Energy Management with Partial Area Coverage

A *partial coverage* variation of the joint framework was developed. This way, network service is provided to active customers only, while access stations having only idle users in their coverage radius can be put to sleep. The model was tested on both cellular and wireless mesh access networks. Results highlighted a further decrease in the network power consumption, which reaches almost -70% (-25% to -35% if compared to the savings achieved with the original formulation) in the cellular examples. Conversely, moderate improvements are experimented for the mesh test scenarios, whose power consumption reduction fluctuates between 9% and 15% with respect to the original JPEM results.

10.1.4 Variations of the Joint Planning and Energy Management Frameworks

Other modifications to the JPEM framework were experimented. Considering the JPEM-CN, a budget limit was introduced to cap the capital costs to a pre-determined amount, while only OpEx were minimized in the objective function. The *Budget* JPEM-CN model proved to be slightly less performant and more computationally complex than the original formulation, even though high energy saving between 45% and 55% are still reached for all the tested scenarios. As far as the JPEM-WMN is concerned, a modified version considered the insertion of a limitation on the number of device on/off state transitions, in order to reduce the energy consumed in the wake-up process. Predictably, setting the maximum transition number at one moderately increased the network energy consumption; in comparison, when access devices are allowed to freely change their state, additional 5% to 9% power saving are achieved. Other JPEM-WMN modifications involve the simulation of the cellular network behavior, by forbidding the installation of mesh routers and thus eliminating the typical mesh network multi-hop capability, and the introduction of variability in the backbone link capacity.

10.1.5 Heuristic Resoution

An heuristic procedure was developed to obtain results in a short amount of time and allow the resolution of real-size scenarios. Through the analysis of the BS activation pattern during the daily peak and off-peak time periods, a partial topology is provided as input to the JPEM-CN and integrated to form a feasible solution. Numerical tests on small cellular scenarios showed that the heuristic approach is close to the JPEM-CN framework behavior, producing as output objective function values only 2% to 5% greater than the joint formulation ones. Real-size instances were successfully solved with two variations of the same heuristic: in one case, better final solutions were provided while, in the other case, the resolution time was strongly reduced. Generally, the heuristic proved to be effective and fast in solving most of the test instances; in particular, if an optimality gap of 3% is set when the biggest scenarios are considered, the solution time never exceeds the hour.

10.2 Future developments

As regards future work, several refinements of the presented results are possible. Even though the JPEM focuses on a *cell sleeping* energy saving mechanism, other operational issues could be considered as, for example, on-line antenna tilting or cell coverage zooming. An extremely interesting future development would consider access devices powered by renewable energy (solar or wind, for example) or by a combination of clean energies and a backup battery. User mobility could also be taken into account by developing a real time on-line operation management model.

A very innovative continuation of the research project would consists in the further exploration of the *partial coverage opportunity for data networks* (as in Capone *et al.*, 2012a). The main idea is that of allowing independent network configurations for data and signaling systems. Coverage gaps in inactive areas are permitted for the data network; on the other hand, the signaling network, which is static and guarantees full coverage to the service area, is able to detect new active users and provide them with network capacity by dynamically switching on data devices (if necessary). The interaction of signaling and data systems would be studied, as well as the effective power consumption and offered connection quality.

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